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BRITTLE MATERIALS DESIGN, HIGH TEMPERATURE GAS TURBINE

Technical Report By:

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ABSTRACT

Modifications in the procedure for hot spin testing ceramic rotors resulted in several changes. The metal curvic spacer, used for mounting the ceramic turbine rotor on the test shaft, was replaced with a ceramic spacer. In addition, curvic coupling teeth were machined on inlet and exit sides of all rotors to accommodate change to a metal curvic washer for piloting of the rotor tie bolt. The short tie bolt for mounting the ceramic rotor to the hot spin test rig shaft was replaced with a long tie bolt as used in engine testing to provide margin for thermal expansion mismatch. The insulated nose cone used in the hot spin test rig was modified to redirect cooling air onto the metal curvic adapter for reduced temperature to relieve ceramic curvic tooth cracking. The complete surface area of the ceramic rotor hub was polished, in contrast to previous polishing of the centerbore and throat areas only. Of twenty-five rotors being proposed for hot testing, ten were inspected by dye-penetrant methods, dimensionally inspected, and curvic coupling contact patterns checked. Five have now completed hot testing; six are ready for test, and the remainder are in processing.

Four ceramic turbine rotors and one rotor hub were qualified for hot testing in the cold spin pit at 55,000 rpm, and three rotors and two rotor hubs were qualified to 70,000 rpm. Blades were lost on all rotors qualified to 70,000 rpm because of gross flaws in the blade cross section. From four to eleven blades per rotor were lost in qualification testing.

Six rotors were subjected to a twenty-five hour durability test in the hot spin test rig at 50,000 rpm and 1800°F rim temperature. Four rotors completed the test and two failed during acceleration to test speed. In several instances, post test rotor inspection revealed presence of curvic tooth cracking after disassembly from the test shaft. One of the successful rotors was operated an additional 175 hours to complete the objective of 200 hours at 1800°F rim temperature over a simulated duty cycle speed schedule.

FOREWORD

This report is the fourteenth technical report of the "Brittle Materials Design, High Temperature Gas Turbine" program initiated by the Defense Advanced Research Projects Agency, DARPA Order Number 1849, and Contract Number DAAG-46-71-C-0162. This is an incrementally-funded seven year program.

This report covers processing, testing, and evaluation of a group of twenty-five duo-density ceramic turbine rotors, which are the final output of the iterative design and materials development program described in prior reports.

Since this is an iterative design and materials development program, design concepts and materials selection and/or properties presented in this report will probably not be those finally utilized. Thus all design and property data contained in the semi-annual reports must be considered tentative, and the reports should be considered to be illustrative of the design, materials, processing, and NDE techniques being developed for brittle materials.

The principal investigator of this program is Mr. A. F. McLean, Ford Motor Company, and the technical monitors of this work are E. S. Wright, E. M. Lenoe, and R. N. Katz, AMMRC.

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1.0 INTRODUCTION

In July, 1971, the Defense Advanced Research Projects Agency of the Department of Defense jointly sponsored a program with Ford Motor Company to develop the use of brittle materials for engineering applications. The major program goal was to prove by a practical demonstration that efforts in ceramic design, materials, fabrication, testing and evaluation could be drawn together and developed to establish the usefulness of brittle materials in demanding high temperature structural applications.

The gas turbine engine, utilizing uncooled ceramic components in the hot flow path, was chosen as the vehicle for this demonstration. The progress of the gas turbine engine has been and continues to be closely related to the development of materials capable of withstanding the engine's environment at high operating temperature. Since the early days of the jet engine, new metals have been developed which allowed a gradual increase in operating temperatures. Today's nickel-chrome superalloys are in use, without cooling, at turbine inlet gas temperatures of 1800°F. However, there is considerable incentive to further increase turbine inlet temperature in order to improve specific air and fuel consumptions. The use of ceramics in the gas turbine engine promises to make a major step in increasing turbine inlet temperature to 2500°F. Such an engine offers significant advances in efficiency, power per unit weight, cost, exhaust emissions, materials utilization and fuel utilization. Successful application of ceramics to the gas turbine would therefore not only have military significance, but would also greatly influence our national concerns of air pollution, utilization of material resources, and the energy crisis.

At the program beginning, the application of ceramics was planned for two gas turbine engines of greatly different size. One was a small vehicular turbine of about 200 HP (contractor Ford) and the other was a large stationary turbine of about 30 MW (subcontractor Westinghouse). In the vehicular turbine project, the plan was to develop an entire ceramic hot flow path including the highly stressed turbine rotors. In the stationary turbine project, the engine was so large that plans were confined to the development of ceramic first stage vanes, and design studies of ceramic rotors.

It should be noted that both the contractor and subcontractor had in-house research programs in this area prior to initiation of this program. Silicon nitride and silicon carbide had been selected as the primary material candidates. Preliminary design concepts were in existence and, in the case of the vehicular engine, hardware had been built and testing initiated.

One difference in philosophy between the two projects is worth noting. Because the ceramic materials, fabrication processes, and designs were not developed, the vehicular turbine engine was designed as an experimental unit and featured ease of replacement of ceramic components. Iterative developments in a component's ceramic material, process, or design can therefore be engine-evaluated fairly rapidly. This work can then parallel and augment the time-consuming efforts on material and component characterization, stress analysis, heat transfer analysis, etc. Some risk of damage to other components is present when following this approach, but this is considered out-weighed by the more rapid acquisition of actual test information. On the other hand, the stationary turbine engine is so large, so expensive to test, and

contains such costly and long lead-time components which could be damaged or lost by premature failure, that very careful material and design work must be performed to minimize the possibility of expensive, time-consuming failures during rig testing and, even more critically, during engine testing. These anticipated difficulties in applying ceramics to a large stationary turbine engine were substantiated to the extent that the scope of work for the stationary turbine project was revised to demonstrate ceramic stator vanes in a static test rig rather than the formidable task of testing in an actual 30 MW test turbine engine(8). The stationary turbine project was completed in 1976 with the testing of ceramic stator vanes in a static test rig for 100 cycles up to temperatures of 2500°F. The Westinghouse final reports on the stationary turbine project have been published(12). This report and future reports under this contract will therefore deal entirely with the vehicular turbine project.

The principal objective of the Vehicular Turbine Project was to develop ceramic components and demonstrate them in a 200-HP size high temperature vehicular gas turbine engine. The entire hot flow path will comprise uncooled parts. The attainment of this objective will be demonstrated by 200 hours of operation over a representative duty cycle at turbine inlet temperatures of up to 2500°F. Successful completion of this program objective will not only demonstrate that ceramics are viable structural engineering materials, but will also represent a significant breakthrough by removing the temperature barrier which has for so long held back more widespread use of the small gas turbine engine.

Development of the small vehicular regenerative gas turbine engine using superalloy materials has been motivated by its potentially superior characteristics when compared with the piston engine. These include:

— Continuous combustion with inherently low exhaust emissions

— Multi-fuel capability

— Simple machine — fewer moving parts

— Potentially very reliable and durable

— Low maintenance

— Smooth, vibration-free production of power

— Low oil consumption

— Good cold starting capabilities

— Rapid warm-up time

With such impressive potential, the gas turbine engine using superalloys has been under investigation by every major on-highway and off-highway vehicle manufacturer in the world, and, in November 1976, was selected by the U.S. Army as the engine for the XM1 tank.

In addition, the small gas turbine engine without exhaust heat recovery (i.e., non-regenerative) is an existing proven type of power plant widely used for auxiliary power generation, emergency standby and continuous power for generator sets, pump and compressor drives, air supply units, industrial power plants, aircraft turbo-props, helicopter engines, aircraft jet engines, marine engines, small portable power plants, total energy systems, and hydrofoil craft engines. While this variety of applications of the small gas turbine using superalloys is impressive, more widespread use of this type engine has been hampered by two major barriers, efficiency and cost. This is particularly so in the case of high volume automotive applications.

Since the gas turbine is a heat engine, efficiency is directly related to cycle temperature. In current small gas turbines, maximum temperature is limited not by combustion, which at stoichiometric fuel/air ratios could produce temperatures well in excess of 3500°F, but by the capabilities of the hot component materials. Today, nickel-chrome superalloys are used in small gas turbines where blade cooling is impractical, and this limits maximum turbine inlet gas temperature to about 1800°F. At this temperature limit, and considering state-of-the-art component efficiencies, the potential overall efficiency of the small regenerative gas turbine is not significantly better than that of the gasoline engine and not as good as the Diesel. On the other hand a ceramic gas turbine engine operating at 2500°F will have fuel economies superior to the conventional Diesel at significant weight savings.

The other major barrier is cost and this too is strongly related to the hot component materials. Nickel-chrome superalloys, and more significantly cobalt based superalloys which meet typical turbine engine specifications, contain strategic materials not found in this country and cost well over $5/lb. This is an excessive cost with respect to high volume applications such as trucks or automobiles.

High temperature ceramics such as silicon nitride or silicon carbide, on the other hand, are made from readily available and vastly abundant raw materials and show promise of significantly reduced cost compared to superalloys, probably by at least an order of magnitude.

Thus, successful application of ceramics to the small turbine engine, with an associated quantum jump to 2500°F would not only offer all of the attributes listed earlier, but in addition would offer superior fuel economy and less weight at competitive cost with the piston engine.

The vehicular project is organized to design and develop an entire ceramic hot flow path for a high temperature, vehicular gas turbine engine. Figure 1.1 shows a schematic of this experimental regenerative engine, designated model 820. Air is induced through an intake silencer and filter into a radial compressor, and then is compressed and ducted through one side of each of two rotary regenerators. The hot compressed air is then supplied to a combustion chamber where fuel is added and combustion takes place.

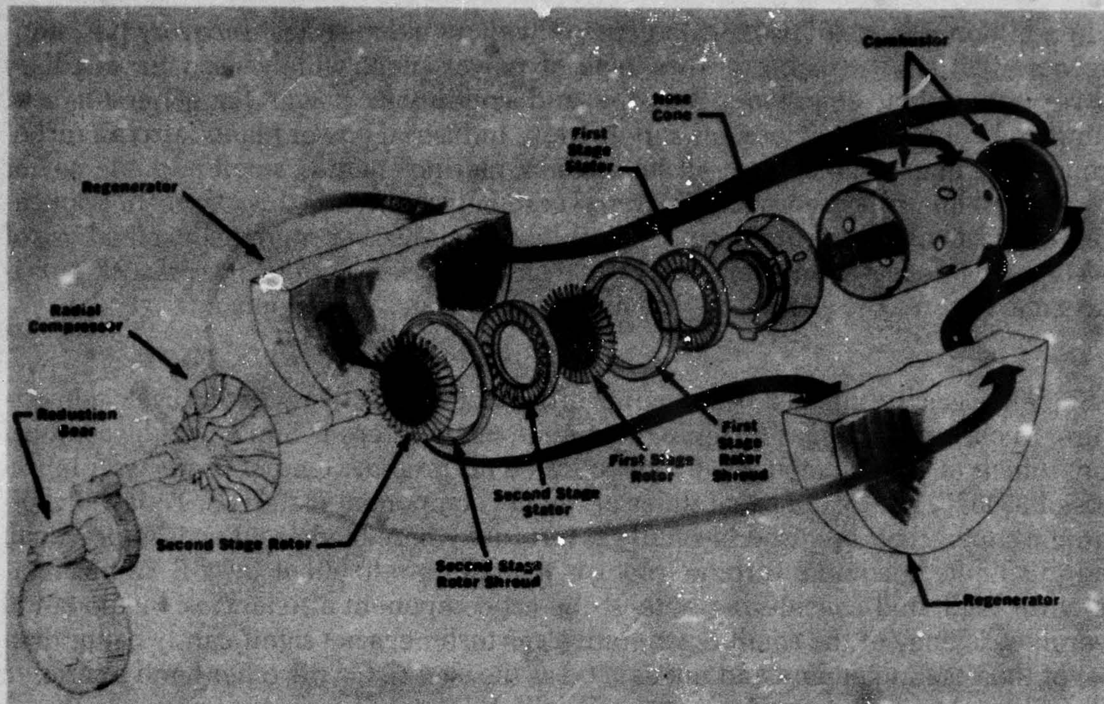


Figure 1.1 — Schematic View of the Vehicular Turbine Engine Flowpath

The hot gas discharging from the combustor is then directed into the turbine stages by a turbine inlet nose cone. The gas then passes through the turbine stages which comprise two turbine stators, each having stationary airfoil blades which direct the gas onto each corresponding turbine rotor. In passing through the turbine, the gas expands and generates work to drive the compressor and supply useful power. The expanded turbine exhaust gas is then ducted through the hot side of each of the two regenerators which, to conserve fuel, transfer much of the exhaust heat back into the compressed air.

The hot flow path components, subject to peak cycle temperature and made out of superalloys in today's gas turbine, are the combustor, the turbine inlet nose cone, the turbine stators, the turbine tip shrouds, and the turbine rotors. These are the areas where the use of ceramics could result in the greatest benefits, therefore these components have been selected for application of ceramics in the vehicular turbine project.

Successful development of the entire ceramic flow path, as demonstrated in a high temperature vehicular gas turbine engine, will involve a complex iterative development. Figure 1.2 shows a block diagram flow chart, including the feedback loops, of the major factors involved, and serves to illustrate the magnitude of this complex and comprehensive iterative development program. Of particular importance is the interrelationship of design, materials development, ceramic processes, component rig testing, engine testing, non-destructive evaluation and failure analysis.

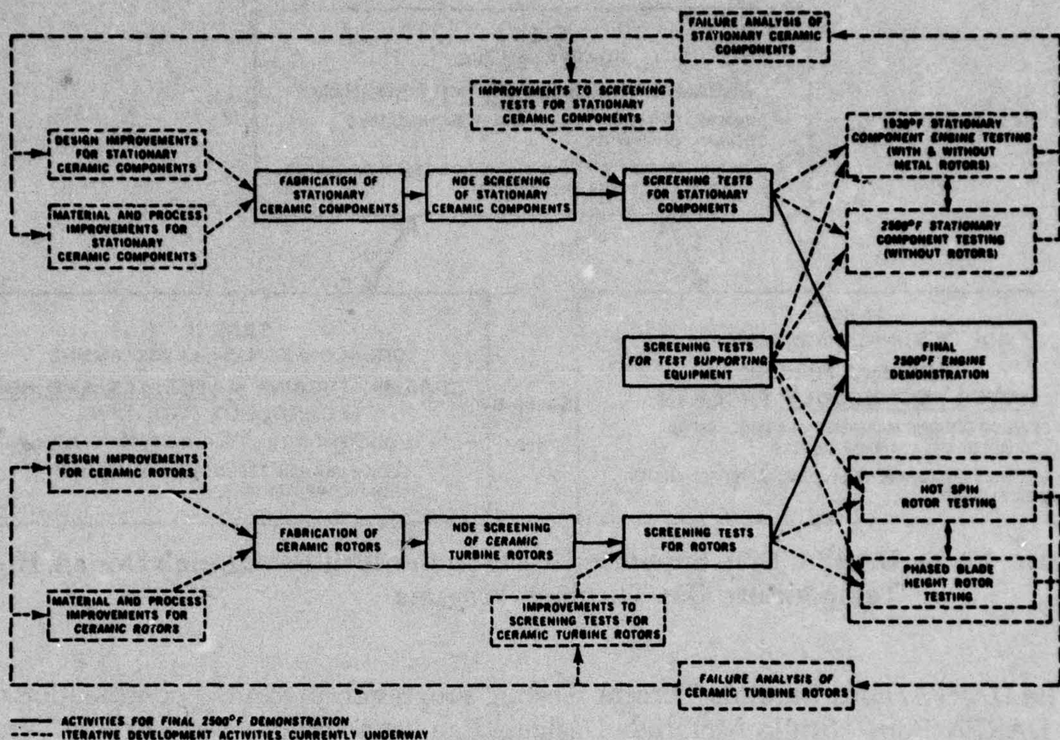


Figure 1.2 — DARPA/DOE/Ford Ceramic Turbine Program — Major Project and Development Loops

One cannot divorce the development of ceramic materials from processes for making parts; no more so can one isolate the design of those parts from how they are made or from what they are made. Likewise, the design of mountings and attachments between metal and ceramic parts within the engine are equally important. Innovation in the control of the environment of critical engine components is another link in the chain. Each of these factors has a relationship with the others, and to obtain success in any one may involve compromises in the others.

Testing plays an important role during the iterative development since it provides a positive, objective way of evaluating the various combinations of factors involved. If successful, the test yields the credibility to move on to the next link in the development chain. If unsuccessful, the test flags a warning and prompts feedback to earlier developments to seek out and solve the problem which has resulted in failure. Finally, all of the links in the chain are evaluated by a complete engine test, by which means the ultimate objective of the program will be demonstrated. It is important then to recognize that this is a systems development program — no single area is independent, but each one feeds into the total iterative system.

In fiscal year 1977, DOE joined forces with DARPA to support the program. and, working closely with NASA-Lewis, supported process development to improve the fabrication of ceramic turbine rotors, and supported some of the work on non-destructive evaluation of ceramics and ceramic materials characterization (Figure 1.3). AMMRC continued to function as the technical monitor of the overall program.

The DOE portion of the fiscal year 1977 program, Tasks II and III in Figure 1.3, is reported in reference 14.

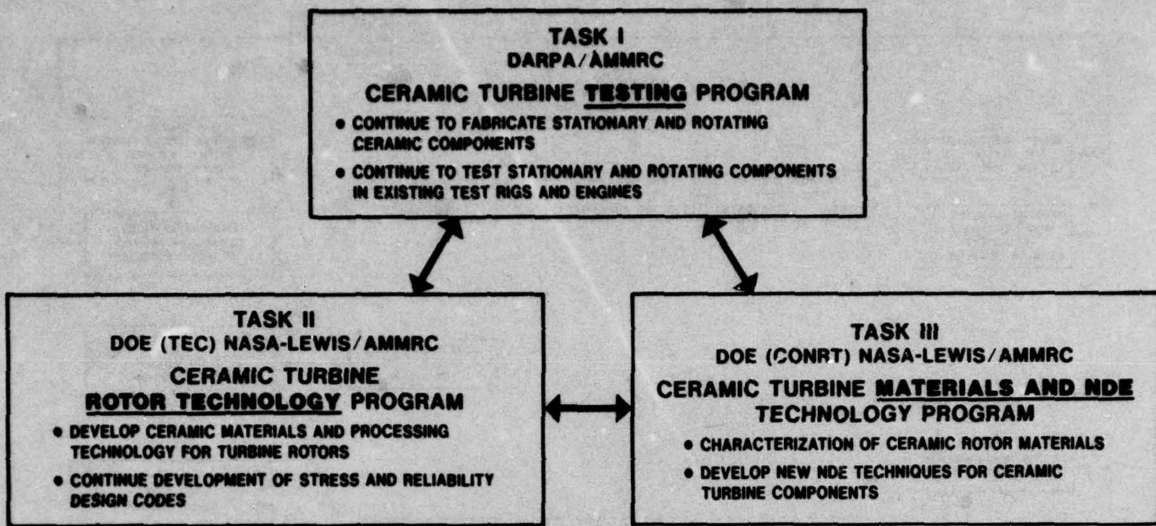


Figure 1.3 — DARPA/DOE Supported Tasks in the "Brittle Materials Design, High Temperature Gas Turbine" Program

The DARPA/Ford Ceramic Turbine Testing Program represents a continuation of the DARPA/Ford "Brittle Materials Design, High Temperature Gas Turbine" Program [1-11]. DARPA's goal remains to show, by a 200 hour demonstration (at temperatures up to 2500°F) of a ceramic gas turbine engine, that ceramic design, materials, fabrication, testing and evaluation can be sufficiently developed to establish the usefulness of brittle materials for demanding engineering applications. During the past fifteen months, the DARPA portion of the program was specifically oriented toward the evaluation of the reliability of state-of-the-art ceramic components which were developed over the previous six years.

Since the beginning of the DARPA/Ford program, a considerable amount of technology has been developed and applied to the design and analysis of ceramic components. Similar progress was made on ceramic material and process development, and on ceramic component and engine testing. During this reporting period, these technologies were evaluated by testing rotating ceramic components for reliability in test rigs and engines. The components were prepared for testing through several inspection stages, including close visual inspection (10-70X), X-ray radiography and dye penetrant inspection where applicable, both before and after machining.

Test and evaluation of ceramic turbine rotor durability was carried out in hot spin test rigs and the 820 turbine engine.

2.0 SUMMARY

2.1 PROGRAM HIGHLIGHTS

This section presents a brief listing of major accomplishments achieved in the DARPA/DOE/Ford program. The numbers in parentheses refer to references listed in Section 4.0 of this report.

- injection molding and slip casting technology was developed to fabricate complex shaped silicon preforms such as blade rings, stators and nose cones which nitride to 2.7g/cc(9,10,11).
- solid state control system designed, built and used to regulate the molding parameters and automate the fabrication of blade rings, stators and nose cones(11).
- nitrogen/hydrogen demand cycle conceived and implemented for nitriding silicon compacts to a density of 2.55-2.7g/cc(9).
- 2.7g/cc injection molded reaction sintered silicon nitride achieved 4 point bend strengths of 43 ksi at 70°F(8) and no time dependent failures at 20-30 ksi and 1900-2000°F for up to 200 hours(10).
- many rotor fabrication approaches were investigated, and discarded or shelved(1-5). Duo-Density silicon nitride rotor concept conceived(2) consisting of reaction bonded silicon nitride blades and a hub of hot pressed silicon nitride.
- hot press bonding technology was developed to produce a 70% yield of duo-density rotors free of flaws induced by hot pressing(11).
- processes for making all ceramic (silicon nitride and/or silicon carbide) parts (combustor, nose cone, stators, rotor tip shrouds and rotors) devised and developed. Many parts of each type made to develop the processes and evaluated by testing(1-11).
- ultrasonic C-scan, acoustic emissions and microfocus X-ray techniques investigated for NDE of ceramic components(1-6,11).
- rotor blades and stator vane bend tests, stator shroud test and 10-light qualification tests developed as screening tests for ceramic components(6,8-11).
- 2.7g/cc stator vanes survived over 9000 cycles to 2700°F on the Thermal Shock Rig(8).
- a probabilistic design technique for ceramics was developed and applied to ceramic rotors(5).
- hot pressed Si_3N_4 rotor hubs demonstrated a characteristic failure speed of 108,500 rpm with a Weibull slope of 14.8 which was in agreement with analytical predictions(10).
- aerodynamic/reliability studies showed a 3-stage turbine at 50,000 rpm had a higher reliability than a 2-stage at 64,000 rpm for the same power and efficiency(11).
- all stationary ceramic components successfully met the program durability goal(14).

Program Goal	Hours at 1930°F		Hours at 2500°F		Total Hours
	175	+	25	=	200
Reaction Bonded SiC Combustor	175		26		201
Reaction Sintered Si_3N_4 Nose Cone	175		26		201
Reaction Sintered Si_3N_4 Stators	175		26		201
Reaction Bonded SiC Stator	176		29		205
Reaction Sintered Si_3N_4 Shrouds	175		26		201

- duo-density silicon nitride rotor #1195 engine tested for 10 hours at 2200°F turbine inlet temperature and 45,000 rpm without failure; rotor additionally tested, successfully, for 25 hours at 2250°F, 50,000 rpm, plus 1½ hours at 2500°F, 50,000 rpm; failure occurred during a shutdown due to 790°F overtemperature in the vicinity of the curvic coupling (14).

- four duo-density silicon nitride rotors successfully completed a twenty-five hour durability test at 50,000 rpm, and 1800°F rim temperature in the hot spin test rig.*

- one of the successful 25 hour test rotors was operated an additional 175 hours over a variable speed duty cycle and 1800°F rim temperature to complete the program 200 hour durability rotor goal.*

Note: Refer to this report for items noted *.

2.2 CUMULATIVE PROGRAM SUMMARY

To meet the program objectives, the work has been divided into two major tasks:

1. Ceramic Component Development

2. Materials Technology

A review of progress throughout the history of this program and present status in each of these tasks is summarized in Section 2.2.1 and 2.2.2.

2.2.1 CERAMIC COMPONENT DEVELOPMENT

Two catagories of ceramic components are under development: rotating parts (i.e., ceramic rotors), and stationary parts (i.e., ceramic stators, rotor tip shrouds, nose cones, and combustors). In this iterative development, each component will pass through various phases comprising design and analysis, materials and fabrication, and testing.

CERAMIC ROTORS

The development of the ceramic turbine rotor is by far the most difficult task in the DARPA program. This is because of:

- The very complex shape of the turbine rotor forcing the devlopment of new and unique fabrication capabilities.
- The high centrifugal stresses associated with high maximum rotor speeds.
- The high thermal stresses and associated thermal fatigue resulting from both steady and transient high temperature gradients from the rotor rim to the rotor hub.
- The hostile environment associated with the products of combustion from the combustor.
- The high temperature of the uncooled blades resulting from turbine inlet gas temperatures of 2500°F.

Progress and Status

- Fully dense Si_3N_4 first and second stage integral rotors were designed and analyzed (1,2,3,4).
- A method of attaching rotors was conceived and designed (1,2).
- The following approaches for making integral rotors were investigated but discontinued:
  - — Direct hot pressing of an integral Si_3N_4 rotor (1).
  - — Ultrasonic machining of a rotor from a hot pressed Si_3N_4 billet (1,2,3,).
  - — Hot pressing an assembly of individually hot pressed Si_3N_4 blades (1,2).
  - — Pseudo-isostatic hot pressing of an injection molded Si_3N_4 preform (1,2,3).

— Hot pressing using comformable tooling of preformed Si_3N_4 blades and hub (2,3,4).
— Fabrication of a dense SiC blade ring by chemical vapor deposition (1,2,3,4).
— Electric discharge machining of a rotor from a hot pressed SiC billet (2,3,4).

- A "duo-density" Si_3N_4 ceramic rotor was conceived and designed (3).
- Tooling to injection mold Si_3N_4 blade rings was designed and procured (3).
- Several hundred hot press bonding of duo-density rotors have been carried out (10). These have progressed from rotors with flat-sided hubs to fully-contoured hubs made simultaneously with the hot press bonding operation. Prior severe blade ring distortion problems have been solved by using a double blade fill to support the blade ring during bonding. In addition, the diffusion bond has been improved as evidenced by microstructural examination. Experiments were conducted using magnesium nitrate instead of magnesium oxide as a densification aid. Excellent bonding and density were achieved but strength was deficient. Successful modifications were made to the graphite wedge system to reduce blade ring cracking and tearing problems. Problems which remain are occasional blade ring and rim cracking (4,5,6,7,8).
- Over 110 cold spin tests resulted in blade failures over a range of speeds, some of which exceeded full speed requirements of the new Design D' blading. However, an improvement in consistency is required if a reasonable yield from the blade ring fabrication process is to be achieved. This emphasizes the need for three-dimensional blade stress analysis as well as development of a higher strength, better quality blade material. Cold spin testing of rotor hubs of hot pressed Si_3N_4 showed a characteristic failure speed of 115,965 rpm with a Weibull rpm slope of 17.66(7). Several hot pressed hubs, made by the hot press bonding process, were cold spun to destruction, and showed results consistent with hot pressed hubs fabricated separately (8). A high speed motion picture study (3000 frames/sec) was conducted of a turbine rotor failure in the cold spin pit (8).
- A three dimensional model of the rotor blade along with heat transfer coefficients has been generated for thermal and stress analysis (5,6,8).
- Development of better quality blade rings continues. X-ray radiography of green parts has proved effective in detecting major flaws. Slip cast Si_3N_4 test bars having a density 2.7gm/cc show four point MOR of 40,000 psi. Processes to slip cast a rotor blade ring have been investigated as have methods of achieving 2.7gm/cc density with injection molded material (6,7,8).
- Thermal shock testing simulating the engine light-off condition was conducted on rotor blade rings for approximately 2,500 cycles without damage (5,6).
- A technique to evaluate probability of failure using Weibull's theories was developed and applied to ceramic rotors (5).
- A test rig was designed and built to simulate the engine for hot spin testing of ceramic rotors (3,4,5). A set of low quality duo-density rotors was spin tested to 20% speed and 1950°F for a short time before failure, believed due to an axial rub (7).
- A revised rotor design (Design D) was conceived, using common rotors at first and second stage locations (7).

- A lower stress version of the Design D rotor, designated Design D′, has been designed using radially stacked blade sections. Blade centrifugal stresses were reduced from 21,000 psi in Design D to 13,181 psi in Design D′ (8).
- The rotor test rig was rebuilt and testing initiated to evaluate the rotor attachment mechanism and the curvic coupling mounting design. Hot-pressed Si_3N_4 rotor hubs were subjected to 10 operating cycles from 900 to 1950°F, during a 3-3/4 hour test, without damage (8).
- Design codes for ceramics were refined to include nonlinear thermal properties of materials and to allow for the specification of the MOR-strength and Weibull "m" requirements for a given failure at a specified loading and reliability level (9,10).
- Rotor hubs were successfully densified and press bonded at both 2% and 3-1/2% MgO levels, resulting in reduction of MgO migration into the blade ring and improved high temperature strength over previous pressings with 5% MgO (9).
- A design C duo-density rotor with a few obviously flawed blades removed was cold spin tested after static oxidation at 1900°F for 200 hours. A single half-blade failure occurred at 53,710 rpm, which corrects to 68,000 rpm or 105% speed for the present shorter bladed Design D′ configuration. The results of a number of spin tests of slip cast Si_3N_4 blade segments were combined to yield a median failure speed of 64,000 rpm (9).
- Over five hundred blade rings, previous to Design D′, were injection molded for press bonding experiments, cold spin tests, and hot tests (9).
- New tooling to injection mold the lower stressed Design D′ rotor blade rings was received and trial moldings to establish molding parameters were initiated (9).
- Progress has been made in several aspects of the press-bonding step of duo-density rotor fabrication. A problem of excessive deflection of the graphite support structure beneath the rotor assembly, permitting bending and subsequent blade fracture, was solved by the substitution of high modulus hot pressed SiC for the low modulus graphite. Increasing the rate of pressure application also improved the quality of the hub sections (9).
- A new hot spin test rig, designed to improve the turn-around-time in testing turbine rotors, has been constructed, and is currently in the shakedown testing phase. Using gas burners instead of a gas turbine combustion system, this rig simulates the engine environment and was designed to be quickly rebuilt following rotor failures (9,10,11).
- In a program to engine evaluate ceramic rotors having reduced blade length (and less risk of catastrophic failure), two duo-density Si_3N_4 rotors with the blades shortened to 10% of the design length were selected and cold spun to 64,000 rpm (9). These rotors were then hot tested in an engine for 45 minutes at 32,000 rpm and 2000°F turbine inlet temperature without failure (10).
- The aerodynamic design of an increased efficiency turbine, designated Design E, was initiated. Flowpath optimization, a one dimensional stress analysis, and preliminary detailed blade section definition were completed for both the first and second stage turbine stators and rotors (9).
- A process has been developed to slip cast turbine rotor blade rings (9).

- 3-D stress and reliability analyses were performed on preliminary blade configurations for the increased efficiency Design E turbine rotors (10).
- 500 Design D′ blade rings have been injection molded which will nitride to 2.7gm/cc density (10).
- A new fabrication approach, called the 3 piece concept, to make duo-density silicon nitride turbine rotors, was conceived and demonstrated that a significant reduction of applied loads during hot press bonding could be achieved, generally eliminating blade and rim cracking (10).
- Good correlation was demonstrated between predicted cold burst and actual spin test results on nine rotor hubs spun to destruction (10).
- Six available duo-density turbine rotors of imperfect quality were used to check out the hot spin rigs by hot spin testing to failure, with failure speeds ranging from 12,000 rpm to 35,300 rpm at rotor rim temperatures ranging from 1780°F to 2250°F, (corresponding to equivalent estimated blade tip temperatures in an engine of 1930°F to 2400°F) (10).
- A duo-density rotor with flawed blades removed achieved 52,800 rpm in the modified design engine with ceramic stationary flowpath prior to an unscheduled dynamometer shutdown. A maximum turbine inlet temperature of 2650°F was observed during this run. Post inspection showed all ceramic parts to be crack free. The rotor failed during a subsequent run at 50,000 rpm and 2300°F T.I.T. (10).
- Since the Weibull probabilistic method is being used in the design of ceramic turbine rotors, an investigation of various estimation techniques to obtain Weibull parameters from test data was carried out. The method selected and used in this program is the "Maximum Likelihood Estimator" (MLE) method. Confidence intervals in estimating Weibull parameters using the MLE method were computed to vary significantly with the number of samples tested (11).
- An analytical method was prepared, based on the Wiederhorn-Evans approach (11), to predict the time-to-failure of complex, multiaxially-stressed ceramic components such as the ceramic turbine rotor (11).
- Effort to design improved efficiency ceramic turbine stages (Design E) led to the consideration of a 3-stage turbine versus the current 2-stage design. It was shown that, for the same overall level of efficiency, a three stage turbine would have a significantly higher reliability and could operate at 50,000 rpm maximum speed rather than the 64,000 rpm required to obtain the same power output from a two stage turbine. Alternately, for equal levels of overall reliability, the 3-stage design can be expected to be 3-5 percentage points better in aerodynamic efficiency. Further work on improved efficiency Design E turbine stages was terminated as a result of reductions in the overall program (11).
- An automatic control system utilizing solid state logic elements was designed, built and applied to the injection molding of ceramic turbine components, particularly rotor blade rings. The objective was to consistently control such parameters as molding material temperature, die temperature and various sequencing time. The desired setting of each parameter was varied systematically to optimize the molding process for rotor blade rings based on visual and X-ray inspection. In addition to using optimized molding parameters, it was found necessary to clamp the die

accurately to avoid blade root cracks, and to pre-extrude the starting material to avoid unmelted inclusions. A quantity of Design D' rotor blade rings was molded in the 2.7gm/cc density Si_3N_4 material system utilizing these improvements for subse quent processing (11).

- A parametric study of processing hot pressed Si_3N_4 (HPSN) involving Si_3N_4 powder quality, hot pressing additive, powder milling conditions, and hot pressing conditions, was initiated in an effort to improve the expected reliability of duo-density Si_3N_4 turbine rotors. Sixty HPSN billets were made and used to establish Weibull strength data at 1600°F and 2200°F which is representative of the maximum operating temperatures at the rotor bore and bond respectively (11).

- Test bars cut from three-piece duo-density Si_3N_4 rotors showed low strength in the bond between the HPSN hub and the HPSN bonding ring. Failures of this bond in spin tests also confirmed its lack of strength. In parallel, parametric studies on hot pressing Si_3N_4 showed that flat sided HPSN discs could be made at pressures as low as 500 psi. As a result, an improved two-piece, duo-density Si_3N_4 rotor with a simplified hub profile was considered; this would eliminate the troublesome hub/-bonding ring bond and facilitate low hot pressing pressures which should minimize blade ring damage. Ten such two-piece, duo-density Si_3N_4 rotors were hot press bonded at pressures from 500 to 1500 psi using a 3-1/2 w/o MgO additive material for the hub. Three of these had no rim cracks and only minor blade cracking, and have been selected for finish machining and subsequent spin testing (11).

- Development of the hot spin rig continued and resulted in improvements in the failure detector system, temperature measuring system, and burst absorption capability. To check out the latter, a bladeless rotor was accelerated to 64,840 rpm and the temperature gradient increased until failure occurred. The attachment bolt fractured as designed, the ceramic fiber insulation and stainless steel backing absorbed the failure, and the rotor shaft was only slightly scored at the bearing journal. This damage was quickly repaired to demonstrate a relatively fast turnaround time (11).

- Finite element models of a duo-density Si_3N_4 rotor tested in the hot spin rig were made and will be used to calculate temperatures and stresses in the rotor for a given operating speed and rim temperature (11).

- A number of lubricants have been investigated for the rotor ceramic-to-metal curvic coupling including Nickel Ease, Molykote, Electrofilm, Borkote, and Molydisulfide. A problem of limited life at the 1400°F operating temperature resulted in the development of a 1/4 mil thick gold coating on the contacting surfaces of the curvic teeth. Such a coupling has been tested through four complete thermal cycles with no significant deterioration, and will be used in the next engine test of a ceramic rotor (11).

- Controlling the boron nitride thickness during blade fill processing coupled with a modification of the hot press graphite tooling greatly improved the hot press bonding process increasing the yield of flaw free hot press bonding to 70%. This represents the most significant improvement in the yield of hot press bondings to date (14).

- Surface and internal flaws were found in most injection molded reaction sintered silicon nitride blade rings by visual and destructive evaluation (14).

- Ten of eleven duo-density silicon nitride turbine rotors were cold spun to over 50,000 rpm without failing blades — one rotor successfully qualified to over 70,000 rpm after failing one blade at 65,640 rpm (14).

- Seven ceramic rotors were tested in the hot spin rigs accumulating over 26 hours of hot testing. Rotor 1256 operated at 1800°F rim temperature at 50,000 rpm for 18 hours and 42 minutes before failure (14).

- Duo-density rotor 1195 was engine tested for 10 hours at 2200°F turbine inlet temperature and 45,000 rpm without failure; rotor additionally tested successfully, for 25 hours at 2250°F, 50,000 rpm plus 1½ hours at 2500°F, 50,000 rpm. Failure occurred during shutdown (14).

- Ten silicon nitride turbine rotors were inspected by dye-penetrant methods for bond integrity, porosity, densification, and cracking. Also, dimensional inspection, and curvic tooth contact patterns were obtained. Post test rotor inspection revealed presence of curvic coupling tooth cracking after rotor disassembly from the test shaft.*

- Four ceramic rotors and one rotor hub were qualified for hot testing in the cold spin pit at 55,000 rpm. Also, in preparation for hot testing at 64,240 rpm, three rotors and two rotor hubs were cold spin qualified to 70,000 rpm. Some individual rotor blades were lost on all rotors qualified to 70,000 rpm because of gross fabrication flaws*.

- Development of the hot spin test rigs continued with modifications being made to the rotor piloting system, rotor attachment bolt, and insulated nose cone*.

- Six ceramic rotors were subjected to a twenty five hour durability test in the hot spin test rig at 50,000 rpm and 1800°F rim temperature. Four rotors completed the test successfully*.

- One ceramic rotor successfully completed the 200 hour durability objective in the hot spin test rig over a simulated duty cycle speed schedule, with maximum speed of 50,000 rpm, and 1800°F rim temperature*.

CERAMIC STATORS, ROTOR SHROUDS, NOSE CONES, AND COMBUSTORS

While development of the ceramic turbine rotor is the most difficult task, development of the stationary ceramic flow path components is also vitally necessary to meet the objective of running an uncooled 2500°F vehicular turbine engine. In addition, success in designing, fabricating, and testing these ceramic components will have an important impact on the many current applications of the small gas turbine where the use of stationary ceramics alone can be extremely beneficial. The progress and status of these developments is summarized, taking each component in turn.

NOTE: Refer to this report for items noted *.

Progress and Status

Ceramic Stator

- Early Design A first stage stators incorporating the turbine tip shrouds had been designed, made by assembling individual injection molded reaction bonded Si_3N_4 vanes, and tested, revealing short time thermal stress vane failures at the vane root (1).
- Investigation of a number of modified designs led to Design B, with the rotor shroud separated from the stator. Short time thermal stress vane failures at the vane root were eliminated (1).
- In the fabrication of stators, the starting silicon powder, the molding mixture, and the nitriding cycle were optimized for 2.2 gm/cc density reaction bonded Si_3N_4 (2,3).
- Engine and thermal shock testing of first stage Design B stators revealed a longer term vane cracking problem at the vane mid-span. This led to modification of the vane chord, designated the Design C configuration, which solved the vane mid-span cracking problem (3).
- A remaining problem in first and second stage Design B stators was cracking of outer shrouds, believed due to the notch effect between adjacent vanes. To solve this, a one-piece first stage stator (Design C) was designed and tooling was procured (4,5).
- The Design B second stage stator could not be made in one piece due to vane overlap, so an "inverted channel" design was investigated to eliminate notches at the outer diameter. However, engine testing showed that axial cracking of the outer shroud remained a problem (3,4,5,6).
- A 50 hour duty-cycle engine test of the hot flow path components to 1930°F was completed. The assembled first stage Design C stator was in excellent condition; 8 out of 33 vanes in the second stage inverted channel stator had developed fine cracks (6).
- A 100 hour duty-cycle engine test of the hot flow path components (without a second stage stator) to 1930°F was completed. The reaction bonded silicon nitride (2.55 gm/cc density) one piece first stage Design C stator successfully survived this test (7).
- Improvements in materials and processing resulted in the fabrication of flaw free one piece stators of 2.55 gm/cc density (8).
- A test was devised for mechanically loading stator vanes to failure which provided useful information for material and process development (8).
- Thermal shock testing of 2.7 gm/cc density stator vanes revealed no detectable cracking and negligible strength degradation after 9000 cycles of heating to 2700°F and cooling in the thermal shock rig (8).
- Processing of 2.55 gm/cc density injection molded stators continued. Consistently high weight gains (61-62%) have been obtained using the Brew all-metal furnace employing a slow, gradual rate-of-rise cycle, 4% H_2-96% N_2 gas under static pressure, and Si_3N_4 setters and muffles (9).

- An injection molded stator of 2.55 gm/cc density Si_3N_4 survived static testing (no rotors) for 175 hours at 1930°F steady state. Weight gain of the stator was less than 1%, and this stabilized after 10 hours of testing. The stator is in excellent condition (9).
- Testing of stators up to 2500°F in the Flow Path Qualification Test Rig was initiated with over eight hours of testing accumulated at 2500°F (9).
- A reaction bonded silicon carbide stator successfully accumulated 147 hours of testing at 1930°F and remains crack free (10).
- Over nine hours of testing of a silicon nitride stator were accumulated without incident in the modified engine configuration to a maximum turbine inlet temperature of 2650°F (10).
- As a result of funding reductions in the overall program, a short-term attempt to fabricate stationary ceramic components was made and the best available parts were selected for testing. Attempts to injection mold one-piece stators in the 2.7 gm/cc density Si_3N_4 material system were made and a variety of molding parame ters were examined. A number of stators were processed with good vane quality but questionable outer shroud quality (11).
- Three 2.7 gm/cc density Si_3N_4 stators passed mechanical loading tests in the stator vane and outer shroud loading fixtures though one was categorized poor due to visual fillet cracks. This latter one failed the 10-light qualification test. The other two stators passed the 10-light qualification test (11).
- A review was made of earlier durability testing of 2.55 gm/cc density Si_3N_4 stators at 1930°F. The weight gain was a measure of incipient failure. For example, the failures of six 2.55 gm/cc density Si_3N_4 stators were associated with weight gains in excess of 1.9%. This wide variation of weight gain is thought to be due to the variation in open porosity caused during the nitriding cycle. It is expected that this problem will be considerably lessened for higher density 2.7 gm/cc density Si_3N_4 having good quality microstructure (11).
- Over 1000 hours of hot testing was accumulated on ceramic stators during this reporting period (14).
- Ceramic stators of two different materials, injection molded reaction bonded silicon nitride and reaction bonded silicon carbide, have now successfully completed the program durability goal of 200 hours (14).

Ceramic Rotor Shrouds

- Separate first and second stage ceramic rotor shrouds, which are essentially split rings, evolved in the stator change from Design A to Design B (1).
- As a result of rig and engine testing, rotor shrouds made of cold pressed, reaction sintered Si_3N_4 were modified to have flat rather than conical side faces (2).
- Because of occasional cracking, cold pressing was replaced with slip casting for making higher density rotor shrouds, resulting in a 2-3 fold increase in strength (3).
- Slip casting of rotor shrouds solved the cracking problem but revealed a dimensional change problem as a function of operating time. This was solved by incorpo-

ration of nitriding aids, heat treatment cycles, and other changes in the fabrication process which reduced instability to acceptable levels (4,5,6).

- A 50 hour duty cycle engine test of the hot flow path components to 1930°F was completed, after which both first and second stage rotor shrouds were in excellent condition (6).
- A 100 hour duty cycle engine test of the hot flow path components to 1930°F was completed, after which both first and second stage rotor shrouds were in excellent condition (7).
- Further testing of rotor shrouds to 245 hours and over 100 lights showed them to remain crack free and in excellent condition (7).
- Over nine hours of testing slip cast Si_3N_4 rotor tip shrouds were accumulated without incident in the modified engine configuration used for testing a ceramic turbine rotor up to a maximum turbine inlet temperature of 2650°F (11).
- Both ceramic first and second stage rotor tip shrouds successfully completed the program durability goal of 200 hours (14).

Ceramic Combustors.

- Slip cast silicon nitride and various grades of recrystallized silicon carbide (Crystar) were eliminated as ceramic combustor materials (4).
- A thick-walled, reaction bonded silicon carbide (REFEL) combustor successfully completed the 200 hour duty cycle test. A total of 26 hours and 40 minutes was accumulated at a turbine inlet temperature of 2500°F (10). This combustor was also successfully tested in an engine (8).
- Three thin-walled, reaction bonded silicon carbide (REFEL) combustors were successfully qualified over a 10 hour portion of the DARPA duty cycle (10).

Ceramic Nose Cones

- Early Design A nose cones had been designed, made from injection molded reaction sintered Si_3N_4 and tested (1).
- The nose cone was modified to Design B to accommodate the Design B first stage stator. Several Design B nose cones were made and tested in rigs and engines (2).
- Voids in molding nose cones were minimized by preferentially heating the tooling during molding (5).
- Circumferential cracking and axial cracking problems led to pre-slotted, scalloped nose cones designated Design C (3,4,5,6).
- A 50 hour duty cycle engine test of the hot flow path components to 1930°F was completed, after which the Design C nose cone was in excellent condition (7).
- A 100 hour duty cycle engine test of the hot flow path components to 1930°F was completed, after which the Design C nose cone was in excellent condition (7).
- Further testing of the 2.2 gm/cc density nose cone to 221 hours showed it to remain crack free and in excellent condition (7).

- Improvements in materials and processing resulted in the fabrication of flaw free nose cones of 2.55 gm/cc density (8).
- Processing of 2.55 gm/cc density injection molded nose cones continued. Consistently high weight gains (61-62%) have been obtained using the Brew all-metal furnace employing a slow, gradual rate-of-rise cycle, 4% H_2-96% N_2 gas under static pressure, and Si_3N_4 setters and muffles (9).
- Testing of nose cones up to 2500°F in the Flow Path Qualification Test Rig was initiated with over eight hours of testing accumulated at 2500°F (9).
- Over nine hours of testing a silicon nitride nose cone were accumulated without incident in the modified engine configuration to a maximum turbine inlet temperature of 2650°F (10).
- As a result of funding reductions in the overall program, a short-term attempt to fabricate stationary ceramic components was made and the best available parts were selected for testing. A number of Design D nose cones were injection molded in the 2.7 gm/cc density Si_3N_4 material system using an automated molding control system, primarily developed to make high quality rotor blade rings. Nose cones were processed through nitriding and appeared visually good except for fine cracks between the strut and inner nose (11).
- Three 2.7 gm/cc density Si_3N_4 nose cones successfully passed the 10-light qualifica tion test. One of these has accumulated 10 hours of testing at 1930°F (11).
- A slip cast silicon nitride nose cone was fabricated and tested at 1930°F (14).
- An injection molded reaction bonded silicon nitride nose cone successfully completed the program durability goal of 200 hours (14).

2.2.2 MATERIALS TECHNOLOGY

Materials technology forms the basis for component development including component design, component fabrication, material quality in the component as-made, and evaluation by testing. There are three major categories under materials technology — materials engineering data, materials science, and non-destructive evaluation. Progress and present status in each of these areas is summarized below:

Materials Engineering Data

- Techniques were developed and applied for correlating the strength of simple ceramic spin disks with bend test specimens using Weibull probability theories (5).
- Elastic property data as a function of temperature was determined for various grades of silicon nitride and silicon carbide (2,3,4,5,6,7,9).
- The flexural strength vs. temperature of several grades of SiC and Si_3N_4 was determined (3,4,5,6,9,10).
- The compressive strength vs. temperature of hot pressed SiC and hot pressed Si_3N_4 was determined (4).
- Creep in bending at several conditions of stress and temperature was determined for various grades of reaction sintered silicon nitride (4,5,6,9).
- The specific heat vs. temperature of 2.2 gm/cc density reaction sintered Si_3N_4 was measured, as were thermal conductivity and thermal diffusivity vs. temperature for both 2.2 gm/cc and 2.7 gm/cc density reaction sintered Si_3N_4 (4).
- Stress-rupture data was obtained for reaction sintered silicon nitride under several conditions of load and temperature (6,9,10).
- A group of 31 2.7 gm/cc density injection molded Si_3N_4 test bars, made using the best current nitriding cycle and an atmosphere of 4% H_2, 96% N_2, resulted in a Weibull characteristic strength of 44.3 ksi and an m value of 6.8. Additional material development work is aimed at obtaining a higher m value (9).
- The effects of surface finish and post machining heat treatment on the room temperature strength of hot pressed silicon nitride were determined (10).
- The variation in MOR strength of hot pressed silicon nitride was determined from rotor-to-rotor, within one rotor, and as a function of initial material preparation (10).
- Room and elevated temperature flexure strengths of injection molded reaction sintered silicon nitride of 2.7 gm/cc density were determined (10).
- No time dependent failures were observed for 2.7 gm/cc density injection molded reaction sintered silicon nitride during stress-rupture testing for up to 200 hours at stresses of 20-30 ksi and temperatures of 1900-2200°F (10).
- A simple, practical approach, based on the Wiederhorn-Evans (11) theory, was derived to predict the life of a ceramic under load. The only material measurements required are two sets of strength values at two stress rates. For a given material, this would comprise a statistical number of bend tests (preferably > 30) at each of two stress rates for each temperature. Stress-reliability-lifetime design diagrams can then be readily constructed. Comparison of predicted lifetimes using

this method agrees reasonably well with limited published experimental stress rupture data (11).

- Weibull MOR strength parameters were measured for "Refel" reaction bonded SiC at room temperature and five elevated temperatures. In addition, room temperature Weibull strength parameters in tension were measured but, using probablistic methods, did not correlate with the MOR strength data within a 90% confidence band. Suspected parasitic stresses in the tensile test and/or differences in specimen surface quality are being investigated (11).

Materials Science

- A technique was developed and applied to perform quantitative x-ray diffraction analysis of the phases in silicon nitride (2).
- An etching technique was developed and used for the study of the microstructure of several types of reaction sintered silicon nitride (2).
- The relationship of some processing parameters upon the properties of reaction sintered Si_3N_4 were evaluated (3,4,5,6,10).
- The oxidation behavior of 2.2 gm/cc density Si_3N_4 was determined at several different temperatures. The effect of oxidation was found to be reduced when the density of reaction sintered Si_3N_4 increased (3,7).
- The relationship of impurities to strength and creep of reaction sintered silicon nitride was studied, and material was developed having considerably improved creep resistance (4,5,6,9).
- Fractography and slow crack growth studies were performed on reaction sintered SiC (5) and hot pressed Si_3N_4 (6,7).
- The development of sintered Sialon-type materials was initiated (7). The effects of yttria additives have been studied, especially in relation to the formation of glassy phases (8,10).
- A higher density (2.7 gm/cc) molded Si_3N_4 has been developed which will be used for component fabrication. Four point bend strengths of 43 ksi at room temperature were measured (8).
- An experimental study showed that high pressures did not facilitate nitriding of relatively dense silicon compacts. A parallel theoretical study showed that to store sufficient nitrogen within the pores and avoid diffusion, an impractically high pressure would be needed (8).
- Three techniques to improve the oxidation resistance of 2.7 gm/cc density injection molded Si_3N_4 were evaluated (9).
- Nitriding exotherms, resulting in localized silicon temperatures in excess of 1420°C, produced silicon "melt out" with resulting large porosity and lower strength. Eliminating these exotherms by controlling furnace temperature appears to be the key to uniform microstructure, fine porosity and higher strengths (10).
- Work on yttria-containing Sialons showed that melting occurred at about 1200°C whether or not the glassy phase was crystallized. A number of further experiments were conducted to prepare single phase Sialons from either the $Si_3N_4/Al_2O_3/AlN$

or $Si_3N_4/Al_2O_3/AlN/SiO_2$ material systems. Further work on Sialons was terminated as a result of reductions in the overall program (11).

- Use of a programmed temperature/time nitriding cycle resulted in variations of the microstructure of reaction sintered Si_3N_4, depending on furnace load. To correct this, a control system was designed and built to control the furnace temperature/time cycle automatically to maintain a reasonably steady consumption of nitrogen (i.e. nitriding rate). Use of this automatic control was shown to produce 2.7 gm/cc density Si_3N_4 with consistent, high quality microstructure over a wide range of furnace load (11).
- A fabrication technique for turbine components of reaction bonded SiC has been under development by molding a thermoset polymer filled with SiC particles, pyrolyzing the polymer to carbon, then reaction bonding the structure by the infiltration of molten silicon (11).

Non-Destructive Evaluation

- Ultrasonic C-scan techniques were developed and applied to the measurement of internal flaws in turbine ceramics (1,2,3,4).
- Sonic velocity measurements were utilized as a means of quality determination of hot pressed Si_3N_4 (2,3,5,9).
- A computer-aided-ultrasonic system was used to enhance the sensitivity of defect analysis in hot pressed Si_3N_4 (3,4,6).
- Acoustic emission was applied for the detection of crack propagation and the onset of catastrophic failure in ceramic materials (1,2,5,6).
- A method was developed and applied for the detection of small surface cracks in hot pressed Si_3N_4 combining laser scanning with acoustic emission (4).
- X-ray radiography was applied for the detection of internal defects in turbine ceramic components (2,3,4,5). Hidden flaws in as-molded stators and rotor blade rings were located by x-ray radiography (5,6,7). Such NDE of as-molded parts has been used to develop processes to make flaw-free components (8).
- A dye penetrant has been used to detect surface cracks in components made of the 2.55 gm/cc density Si_3N_4 (8).
- A state-of-the-art summary of NDE methods as applied to the ceramic turbine programs was compiled (6).
- 500 injection molded blade rings were examined, most of them in detail using 30X magnification and X-ray radiography NDE techniques (10).
- A blade bend test was applied to a number of rotor blade rings to assess their quality in terms of characteristic failure load and Weibull modulus. A distinct difference was demonstrated between blade rings nitrided in 100% N_2 and those nitrided in a 96% N_2/4% H_2 mixture, with the latter being approximately 30-40% stronger (11).
- Two test fixtures were designed, built and applied for the mechanical loading of stators either to failure or to a pre-determined proof load. One fixture simultaneously loads each stator vane, and the other pressure loads the stator outer shroud.

Testing to a proof load, while not a direct method of detecting flaws, can be considered a form of NDE. From testing several stators in these fixtures, a marked improvement in failure load was shown for 2.7 gm/cc density Si_3N_4 stators as compared to stators made from earlier 2.55 gm/cc density material. In addition, low-load vane failures could be directly related to fillet cracks (11).

- A number of NDE techniques were reviewed for possible application to ceramic turbine components including Microfocus x-ray, infrared thermography, x-ray tomography, an electrostatic method, and holosonics (11).

2.3 FUTURE PLANS

Future plans for the next reporting period will continue to be confined to finish preparation and hot testing of remaining duo-density Si_3N_4 turbine rotors which were made before August 1977. While these rotors are all of questionable quality, it is expected that they will be useful for development of finish preparation methods, ceramic-to-metal attachment techniques, hot spin test rig refinements and, of course, for evaluation of state-of-the-art all-ceramic turbine rotors. Some in-house effort is underway at Ford to continue rotor material and process development; it is recommended that this work be augmented with government support leading to fabrication of improved all-ceramic turbine rotors and their evaluation at 2500°F.

3.0 CERAMIC COMPONENT EVALUATION

3.1 DUO-DENSITY SILICON NITRIDE CERAMIC ROTORS

Summary

Processing of ceramic duo-density turbine rotors continued in preparation for testing in the hot spin test rig. Ten rotors were inspected by dye-penetrant methods for blade ring to hub bond integrity, porosity, densification, and cracking. Dimensional inspection and curvic coupling tooth contact patterns were obtained for the processed rotors. Post-test rotor inspection after successful test runs, has shown presence of curvic coupling tooth cracking after rotor disassembly from the test shaft.

Changes in testing procedure for the hot spin test rig resulted in additional ceramic machining to provide a ceramic curvic spacer to replace the metal part previously used. Incorporating a metal curvic washer into the hot spin rig, for piloting of the rotor tie bolt, resulted in the requirement for machining curvic coupling teeth on both inlet and exit sides of the ceramic rotor. In addition, the complete surface of the ceramic rotor hub is now polished in contrast to the previous practice of only polishing the centerbore and throat areas. Of the twenty-five rotors selected for hot testing; six are ready for test, five have completed hot testing and the remainder are in processing.

Four ceramic rotors and one rotor hub were qualified for hot testing in the cold spin pit at 55,000 rpm. In addition, in preparation for hot testing at 100% design speed (64,240 rpm), three rotors and two rotor hubs were cold spin qualified to 70,000 rpm. Individual rotor blades were lost on all rotors qualified to 70,000 rpm, and in each case gross fabrication flaws were observed in the failed blade cross sections.

The balancing procedure for the hot spin rig rotor assembly was modified as a result of removal of the dummy compressor wheel from the assembly and substitution of a balance ring on the rotor shaft. The balanced rotor-shaft assembly can be installed in the hot spin test rig directly after balancing without disassembly and thus without disturbing the balance achieved.

Development of the hot spin test rigs continued. The rotor piloting system, using a ceramic cone adapter and metal attachment washer for tie bolt piloting, were replaced with a ceramic curvic spacer and metal curvic washer system as used in engine rotor testing. The ceramic cone system provided unreliable rotor piloting because of unpredictable frictional effects. In addition, the short tie bolt designed for the hot spin test rig was replaced with the long bolt design as used with the engine to provide more margin for thermal expansion mismatch between ceramic rotor and metal tie bolt.

Disassembly of two rotors from the shaft after successful tests in the hot spin rig resulted in cracking of the rotor ceramic curvic coupling teeth in contact with the metal curvic adapter. This condition was attributed to excessive metal temperature of the curvic adapter. The temperature of this part was reduced by modification of the insulated nose cone to redirect the cooling air exiting from the rotor tie bolt.

Six ceramic rotors were subjected to a twenty-five-hour durability test in the hot spin rig at 50,000 rpm and 1800°F rim temperature. Four rotors completed the test successfully and two failed during acceleration to test speed. One of the successful rotors was operated for an additional 175 hours at 1800°F rim temperature over a simulated duty cycle speed schedule without failure. In addition, a ceramic rotor hub was operated for twenty-five hours at 64,240 rpm and 1800°F rim temperature to qualify the hot spin test rig for future rotor testing.

In preparation for additional testing of ceramic turbine rotors in the 820 engine, modifications were made to engine hardware to reduce the operating temperature of the metal curvic adapter which mates with the ceramic rotor inlet side curvic coupling teeth. These modifications resulted in a successful test for thirty minutes at 40,000 rpm and 2500°F turbine inlet temperature.

3.1.1 DUO-DENSITY SILICON NITRIDE ROTOR FABRICATION

Introduction

The duo-density ceramic turbine rotor fabrication process is a multi-step forming procedure beginning with an injection molded silicon metal blade ring and ending with diamond grinding the hot pressed silicon nitride rotor hub to finished dimensions. Subsequent to the injection molding step, the blade rings are burned out, to remove the organic binders, and nitrided to convert the silicon to silicon nitride. The blade ring is then encased in a slip cast blade fill and nitrided. The silicon nitride blade fill supports the blades and rim during the subsequent hot pressing step. The hot pressing operation forms the hot pressed hub, from silicon nitride powder, and simultaneously bonds the hub to the reaction bonded silicon nitride blade ring. The final step is diamond grinding the finished contour of the rotor hub and preparation of the rotor for testing. Coupled with these operations is continued usage of non-destructive evaluation techniques to monitor part quality at each process stage.

Basic fabrication (through hot press bonding) of duo-density silicon nitride rotors was stopped during the last reporting period, at which time, twenty-five rotors remained to be finish processed preparatory to hot testing in either the hot spin test rig or 820 engine.

During this reporting period, finish processing of these twenty-five candidate rotors continued, which includes finish machining, and defect and dimensional inspection.

Rotor Finish Machining

As a result of development of testing procedures in the hot spin test rig, it was decided at the end of the last reporting period to utilize the more expensive curvic mounting system for ceramic rotors for subsequent hot spin testing (14). As a result of development of this system, the metal curvic spacer which had connected the ceramic test rotor to the rotor shaft was replaced with a ceramic curvic spacer; both spacers are shown in Figure 3.1. This new ceramic component has a curvic coupling on both ends thus moving the ceramic to metal interface into a lower temperature zone. In addition a metal adapter with a curvic coupling, shown in Figure 3.2, is used on the front side of the test rotor to pilot the rotor tie bolt. As a result of these changes, finish machining of the test rotors was modified to include curvic couplings at each side of the rotor as shown in Figure 3.3. An additional change in the rotor machining was to polish the complete surface area of the rotor hub. With the previous practice of only polishing the centerbore and rotor throat, the unpolished sections of the rotor were found to be not within design specification for a surface finish of less than 10 micro inches AA; thus, the decision was made to polish the entire rotor hub.

The processing steps for finish machining the twenty-five rotors are listed chronologically below and described in detail in a previous report (14).

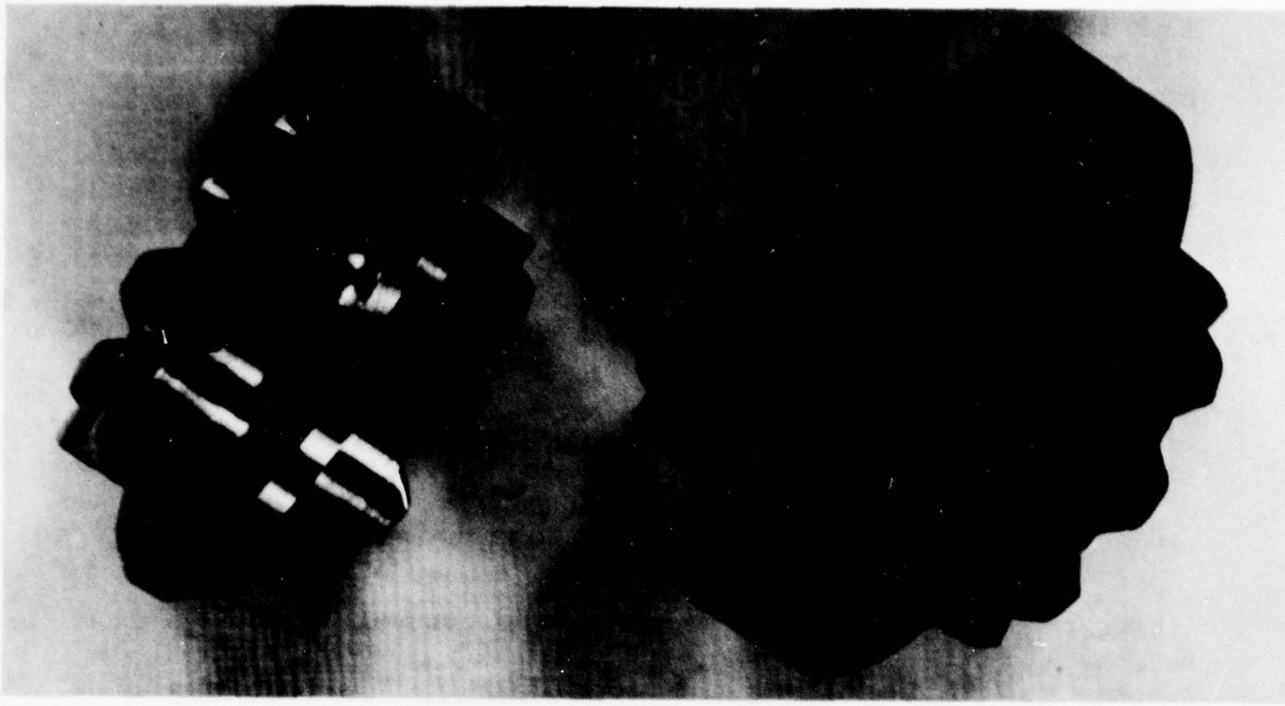


Figure 3.1 — Metal and Ceramic Curvic Spacers.

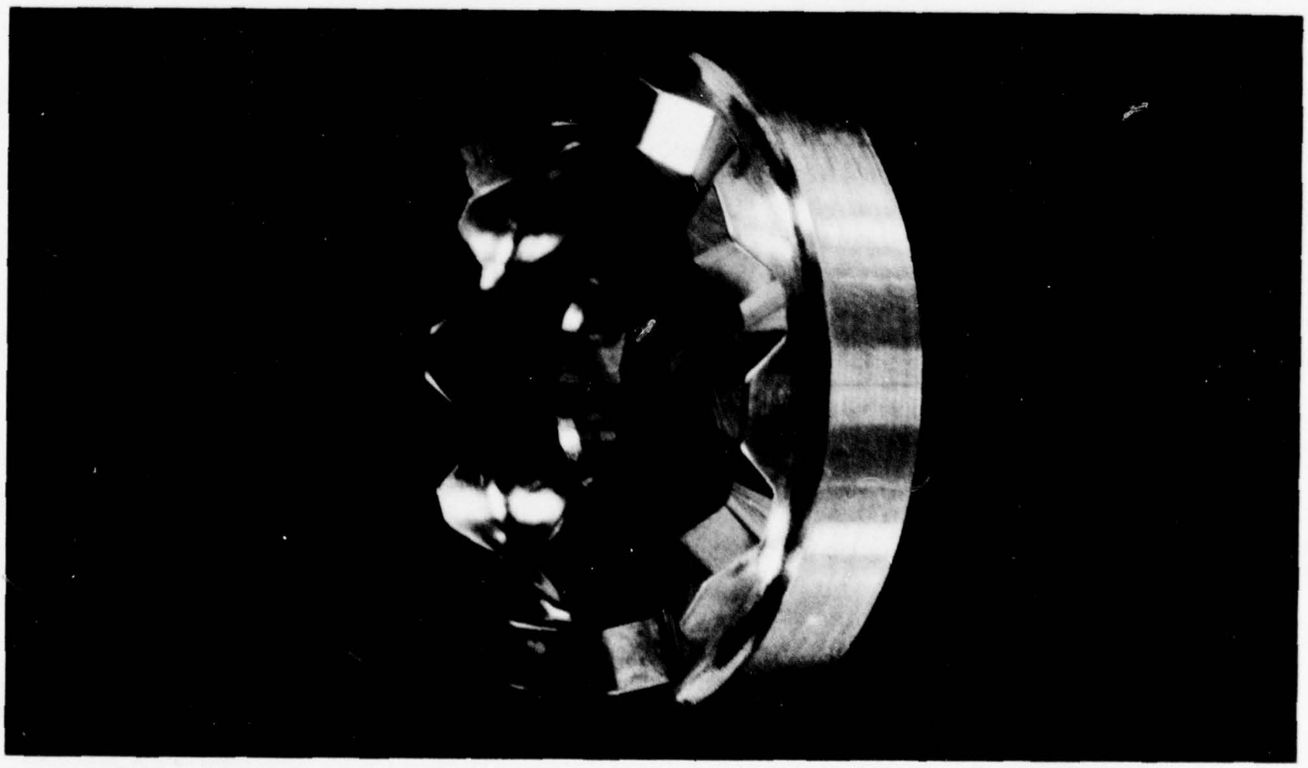


Figure 3.2 — Metal Curvic Adapter.

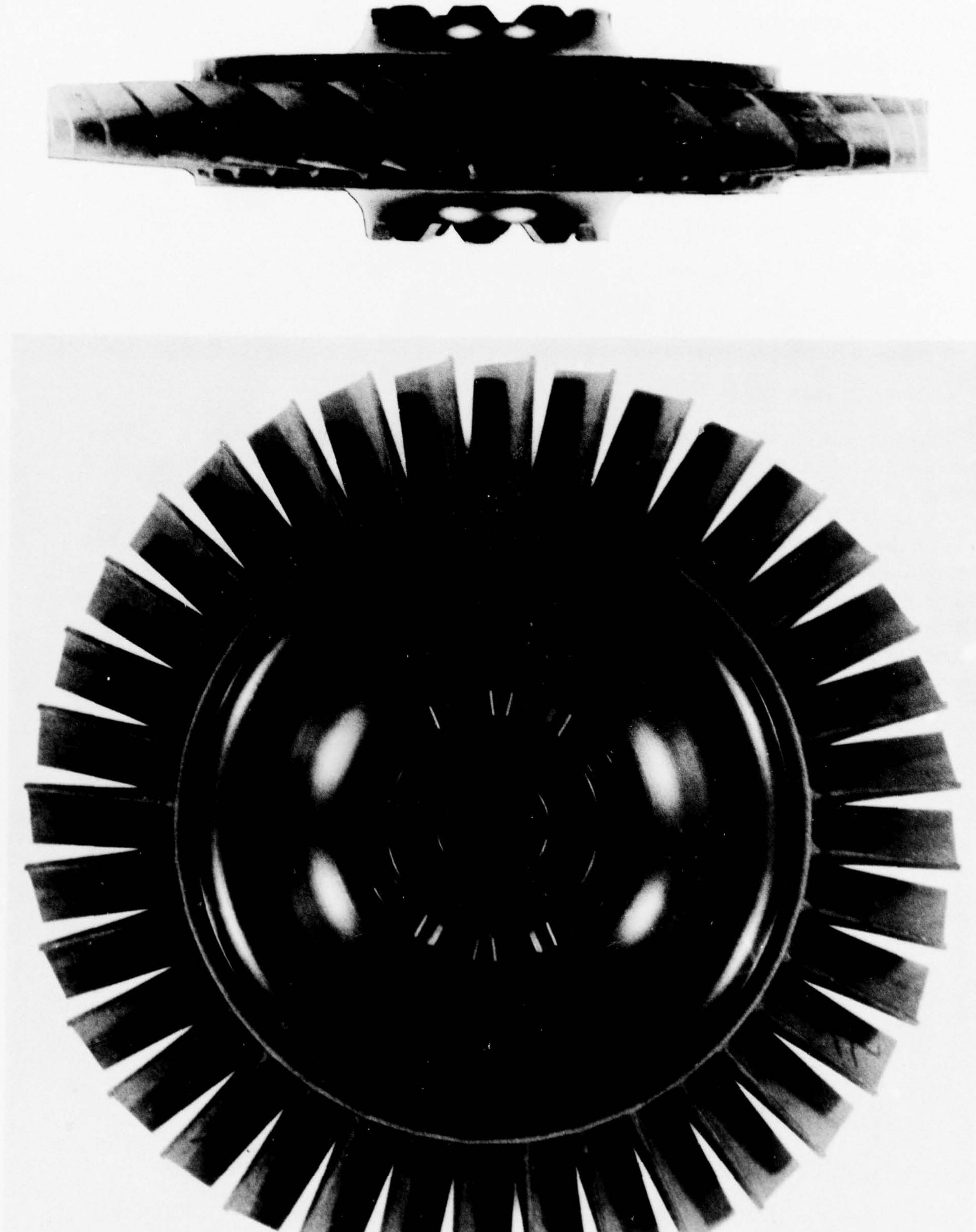


Figure 3.3 —Turbine Rotor with Curvic Couplings.

- Wax Potting of Blades
- Expose Rotor Blade Gage Surfaces
- Axial Extremities of Rotor Faced Off
- Rough and Finish-Grind the Centerbore
- Finish-Grind All Axial Surfaces
- Grind Blade Tip Outside Diameter
- Grind Rotor Hub Extremities
- Finish-Grind Disk Contour & Curvic Coupling Counterbore
- Radius All Edges Except Blades
- Polish Hub Contour and Centerbore
- Remove Wax Blade Potting

The current status of the twenty-five test rotors is shown in Table 3.1. Finish processing will continue as required to complete the hot spin test program on these rotors.

The decision to replace the metal curvic spacer with a ceramic spacer resulted in a temporary shortage of ceramic curvic spacers to join the metal shaft and ceramic test rotor. To resolve this fifteen hot pressed silicon nitride rotor hubs, remaining from the three-piece rotor fabrication development (11), are being machined into ceramic curvic spacers. In the interim, some development work is continuing in the hot spin test rig using converted duo-density rotor hubs as ceramic spacers.

TABLE 3.1
Status of Rotor Finish Machining
(Listed By Rotor Number)

Partially Machined	Ready For Polishing	Finish Machining Complete	Damaged In Finish Processing
1312	1329	1294	1374
1326	1340	1371	1389
1336	1349	1382	
1363	1328	1384	
1373		1392	
1377		1287	
1379		1304	
1387		1306	
1395		1324	
		1368	

Rotor Inspection

Pre-machining inspection consists of a microscopic (30-70x) examination of the rotor for blade damage occurring during the hot pressing operation, and an overall evaluation of the rotor based on a review of the hot pressing and blade ring injection molding parameters. These parameters must be within certain defined limits (14, Vol. 1) in order to qualify a rotor for continued processing and hot testing.

The steps in post-machining inspection and final rotor preparation are listed chronologically below and described in detail in a previous report (14).

- Fluorescent Dye Penetrant Inspection
- Visual Blade Inspection
- Dimensional Inspection
- Proof Test in Vacuum Spin Pit (Cold)
- Grind Curvic Coupling
- Inspect Curvic Coupling
- Radius Curvic Coupling Teeth
- Balance for Hot Test
- Bake Out to Remove Residual Moisture
- Weigh and Photograph

The fluorescent dye penetrant inspection reveals bonding defects, cracks induced during machining, high porosity regions, and mottling effects (13) in the hot pressed silicon nitride disk. Several of these defects are shown in Figure 3.4. The fluorescent dye penetrant technique is also useful in detecting blade root cracks which are difficult to observe under visual examination. Table 3.2 summarizes the results of this examination for the rotors currently through final machining.

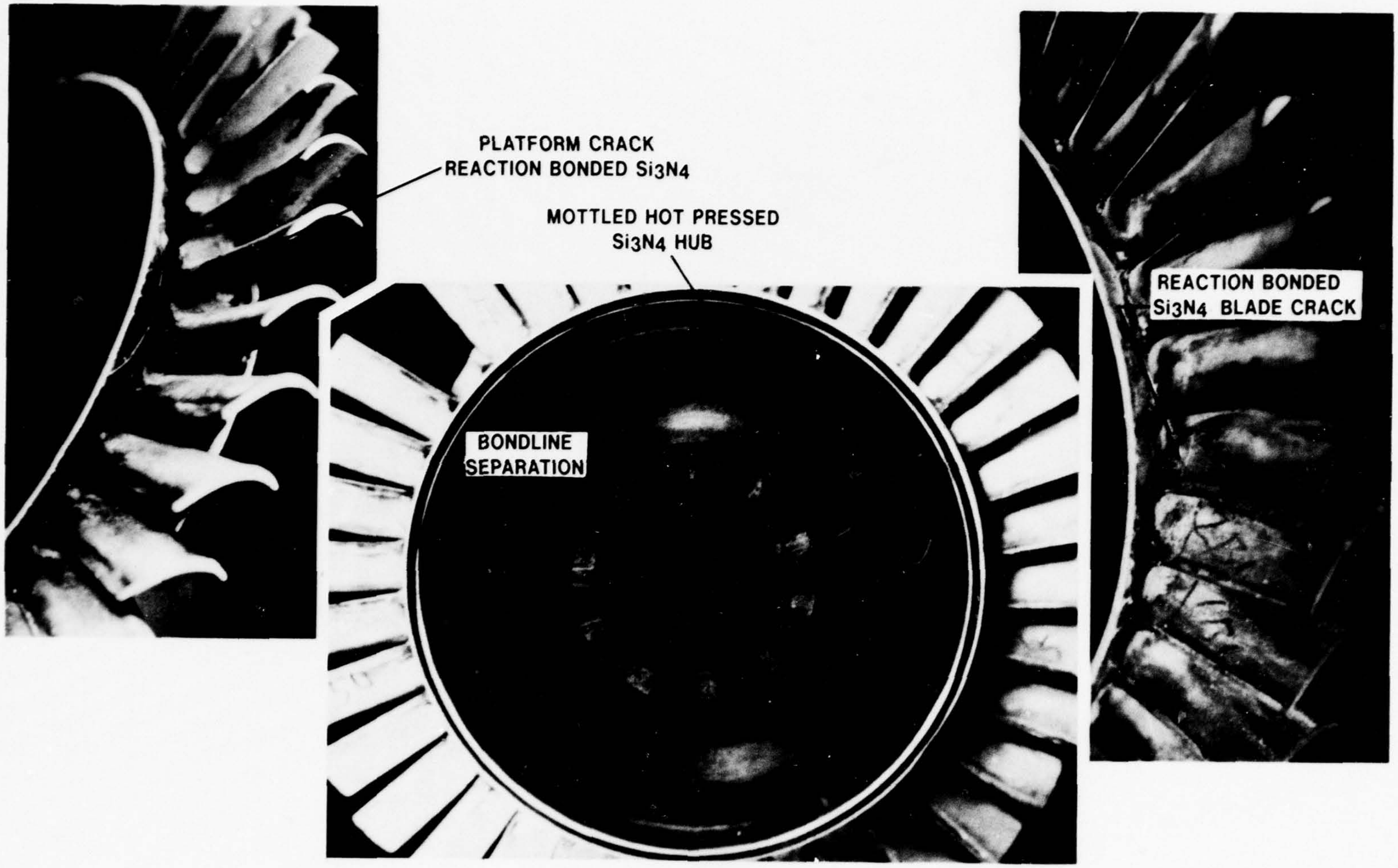


Figure 3.4 — Examples of Turbine Rotor Defects Revealed by Zyglo. T.M.
ROTOR 1355

TABLE 3.2

Pre-Test Inspection

Type of Flaw Detected-Zyglo™

Rotor Number	Bonding Separation	Porosity	Mottling	Curvic Coupling Teeth	Platform Cracks/Chips
1324	Trailing Edge- 0.5 Inches Long	No Indication	No Indication	No Indication	No Indication
1304	Trailing Edge- 360° Intermittent	No Indication	No Indication	No Indication	Eleven Cracks Between Blades Also Graphoil™ Inclusions
1287	Leading Edge- 0.5 Inches Long	No Indication	Both Sides- Primarily Trailing Edge	No Indication	No Indication
1294	Both Sides- 360°	No Indication	Very Mottled Both Sides	No Indication	No Indication
1306	Low Density- Trailing Edge	No Indication	No Indication	No Indication	No Indication
1368	No Indication	No Indication	No Indication	Cracks Spanning Three Teeth	Ten Cracks Between Blades
1371	No Indication	No Indication	Trailing Edge- Slight Trace	No Indication	No Indication
1392	No Indication	No Indication	Trailing Edge- Slight Trace	No Indication	No Indication
1382	No Indication	No Indication	Both Sides	No Indication	Five-Chips Trailing Edge
1384	Trailing Edge-360° Leading Edge-Slight	No Indication	Trailing Edge- Slight Trace	No Indication	No Indication

The final inspection prior to hot testing is a dimensional inspection of the rotor and examination of the curvic coupling tooth contact pattern. The dimensional inspection consists of examination of the areas listed in Table 3.3. While some dimensional deviations may be accepted, critical dimensions are maintained within tolerance or the rotor is rejected. Deviations which would significantly change the stress distribution or level are not accepted. Likewise, dimensional deviations which would cause interference with stationary components or require much stock removal in order to dynamically balance the rotor prior to hot testing are not accepted.

TABLE 3.3
Ceramic Rotor Dimensional Inspection
Summary of Critical Dimensions

- Blade Tip Diameter
- Blade Tip to Centerbore Concentricity
- Blade Platform to Centerbore Concentricity
- Axial Gage Surface Squareness to Centerbore
- Axial Gage Surface Runout
- Axial Location of Blade Platform and Hub in Relation to Gage Surface
- Curvic Coupling Inside and Outside Diameters
- Curvic Coupling to Centerbore Concentricity
- Curvic Coupling Squareness to Centerbore
- Centerbore Diameter
- Hub Width Through Minimum Section

Inspection of the curvic coupling starts with an examination of the tooth contact pattern between mating parts. The contact pattern is established using a non-drying blueing compound which is applied to one set of curvic teeth and transferred to the mating part when gently tapped. This contact pattern is then compared to an acceptance standard. The standard calls for the 0.05 inch contact pattern depth to be centralized and the contact width be at least 90% of the tooth face. Also, the standard requires a bearing pattern on both sides of all teeth. Examples of contact patterns are shown in Figure 3.5. Next, the rotor is checked for squareness and concentricity when mounted on a set of master curvic coupling gages. Concentricity of the rotor and gages is held to within 0.0005 inches while squareness is held to within 0.0015 inches. Finally the spacing between the curvic coupling teeth pitch lines is checked. This dimension controls the axial location of the rotor and is held to within ±0.001 inches.

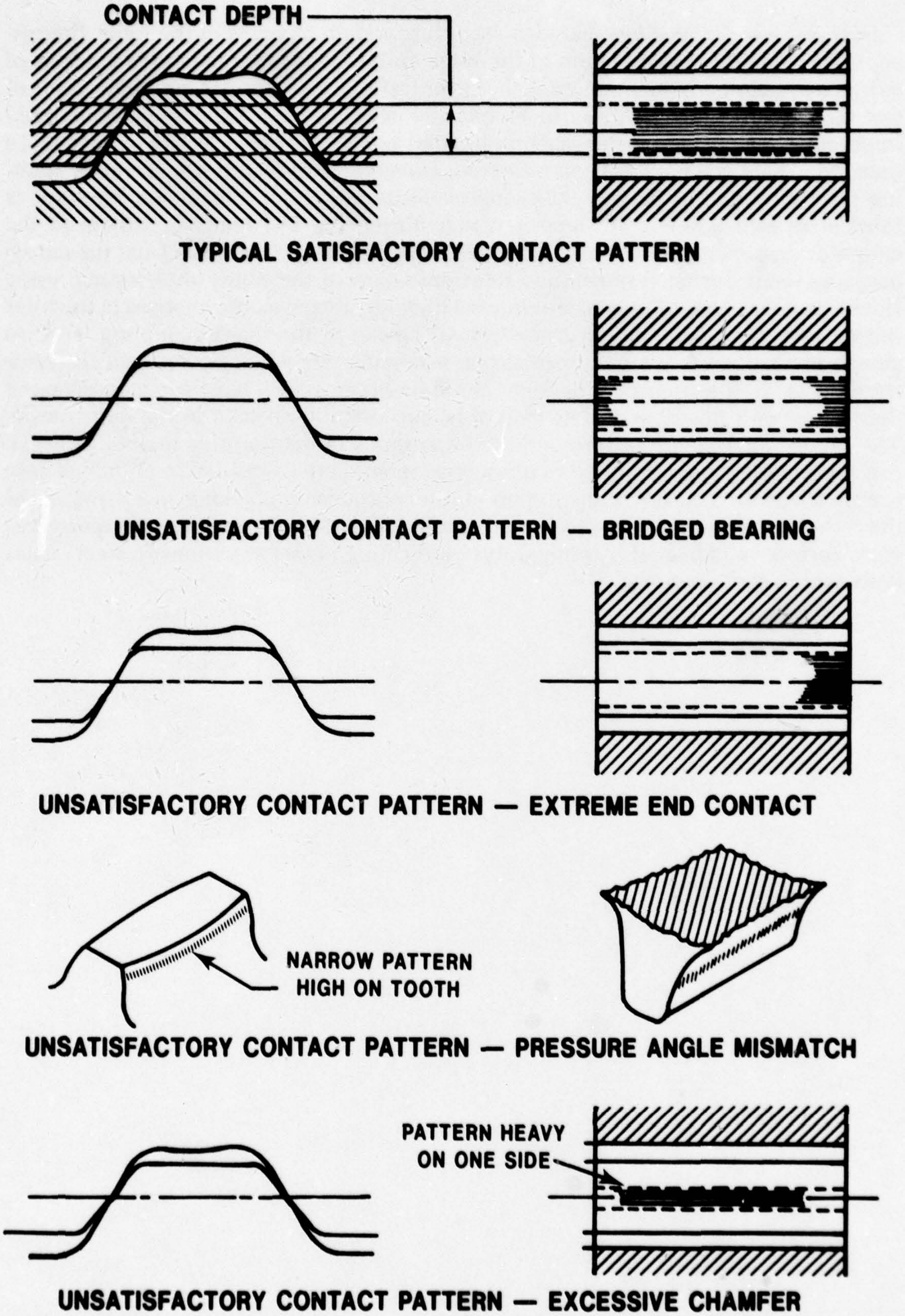
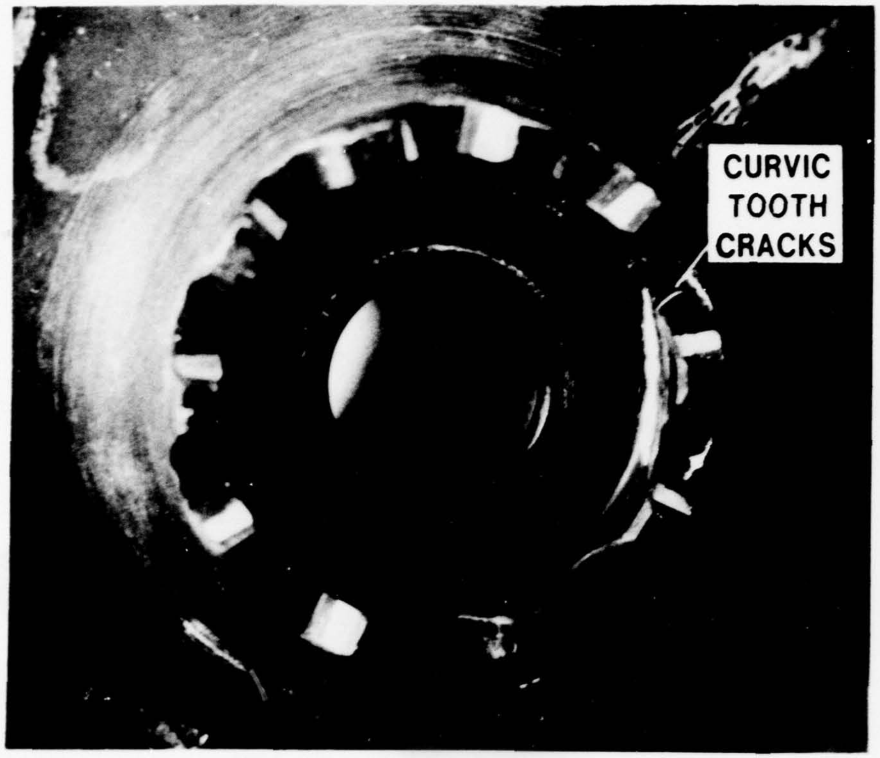


Figure 3.5 — Curvic Tooth Contact Patterns.

Post-test rotor inspection includes recording weight changes in the rotor, fluorescent dye penetrant examination of the rotor, failure analysis, qualitative analysis of α/β phase ratio and examination of hot spin test rig hardware for any indications of test rig initiation of rotor failure. Monitoring of rotor weight change is considered important to determine if the reaction bonded blades are degraded by oxidation. To date, no weight change has been observed. However, two factors are currently limiting the usefulness of the weight change measurement: the rotor metal interface is lubricated with a soft gold deposit which during the test tends to adhere to the ceramic component, and several rotors have spalled small fragments from the curvic coupling teeth during disassembly. Reexamination of the rotor, after testing, using fluorescent dye penetrant is useful in revealing any macroscopic changes in the rotor during test. This examination has revealed cracks in the curvic coupling teeth as shown in Figure 3.6, which appear to be occurring during disassembly of the rotor from the shaft. It is important to detect these flaws because it has been demonstrated that rotors with this type of flaw cannot be successfully retested in the hot spin rig. The failure analysis procedure and the importance of determining qualitatively the α/β phase ratio were described in a previous report (14). Examination of the hot spin test rig hardware consists of inspection of rotor shrouds for cracking, measurement of the rotor attachment bolt for creep, and confirmation that the operating temperatures were correct as indicated by temperature indicating paints at various strategic locations within the assembly.



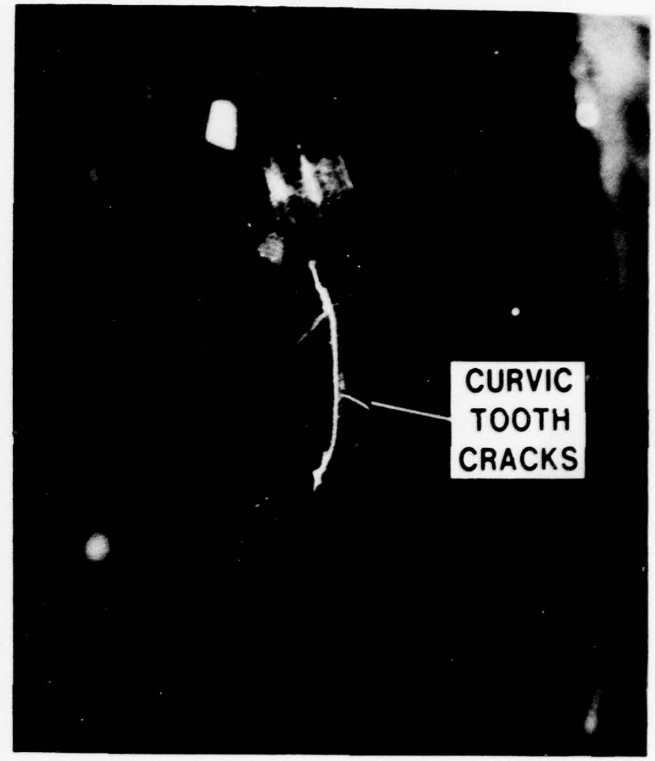


Figure 3.6 — Curvic Tooth Cracks Revealed by Zyglo. T.M.

3.1.2 DUO-DENSITY SILICON NITRIDE ROTOR TESTING

Introduction

During this reporting period work continued on improvement of hot spin test rig reliability, and preparation of the test rig for testing rotors at higher speed and temperature. The plan was to hot spin test six duo-density silicon nitride rotors at a fixed speed and temperature with an objective durability of twenty-five hours on each. The selected speed and temperature was 50,000 rpm and 1800°F rotor rim temperature. Once the six-rotor test was complete, a further objective was to attempt to complete a 200 hour test of a duo-density rotor in the hot spin rig at 1800°F rim temperature and a variable speed duty cycle. Completion of these planned tasks as well as an engine test at 2500°F turbine inlet temperature, constitute major accomplishments during this reporting period.

Cold Spin Qualification

The vacuum spin pit continued to be used to qualify duo-density rotors for subsequent testing in the hot spin rig. The qualifying speed remained at 110% of scheduled hot test speed.

Cold spin test results, summarized in Table 3.4, is a continuation of Table 3.3 in Volume I of the last report (14). The updated data in Table 3.4 includes four rotors and one rotor hub qualified to 55,000 rpm, (for hot testing to 50,000 rpm) and three rotors and two rotor hubs qualified to 70,000 rpm (for hot testing to 64,240 rpm). Some rotor blades were lost from all rotors qualified to 70,000 rpm. In each case, gross flaws in the failed blade cross section were observed. An example of failed blade flaws is shown in Figure 3.7. These flaws have been discussed in Volume 2 of the last report (14), where it was concluded that cold spin blade failures occurring below 90,000 rpm are related to blade gross internal or surface deflects. Rim chipping, reported in Table 3.4, does not appear to be a failure initiating defect.

Turbine Wheel Balancing

To successfully operate a turbine rotor system at typical gas turbine speeds it is necessary to dynamically balance the rotor and shaft assembly as a rigid body to within 0.003 oz-in unbalance in two planes.

The rotor and shaft assembly is shown in Figure 3.8. It consists of a thrust collar, shaft, ceramic curvic spacer, ceramic turbine rotor, metal curvic adapter, tie bolt, and nut. Also shown is a collar, mounted on the shaft with an interference fit, to provide balance material. Not visible is the compression member which is part of the folded attachment bolt concept[1]. A cross sectional view of this arrangement is shown in Figure 3.9.

Imbalance in the rotor and shaft assembly is caused primarily by the rotor itself. The rotor may be statically unbalanced due to irregularities in the blades from the manufacturing process. Also, some defective blades may have been removed by the time the rotor is ready for balancing. If the static imbalance from the rotor were to be

TABLE 3.4

Cold Spin Test Results

Rotor Number	Speed Rpm	Results
1306	16,770	Rim Chipping
	55,000	Rotor Qualified
1304	55,000	Rotor Qualified
1368	55,000	Rotor Qualified
1389	41,500	Rim Chipping
	55,000	Rotor Qualified
1392	64,260	Lost 2 Blades
	66,800	Lost 7 Blades
	66,120	Lost 1 Blade
	70,000	Rotor Qualified
1382	49,750	Rim Chipped
	63,780	Lost 2 Blades
	67,690	Lost 2 Blades
	70,000	Rotor Qualified
1384	20,920	Lost 2 Blades
	48,880	Lost 1½ Blades
	54,370	Lost 1½ Blades
	56,460	Lost 1 Blade
	69,540	Lost 4½ Blades
	70,000	Rotor Qualified
1353 (Hub)	70,000	Qualified
1290 (Hub)	70,000	Qualified
1301 (Hub)	55,000	Qualified

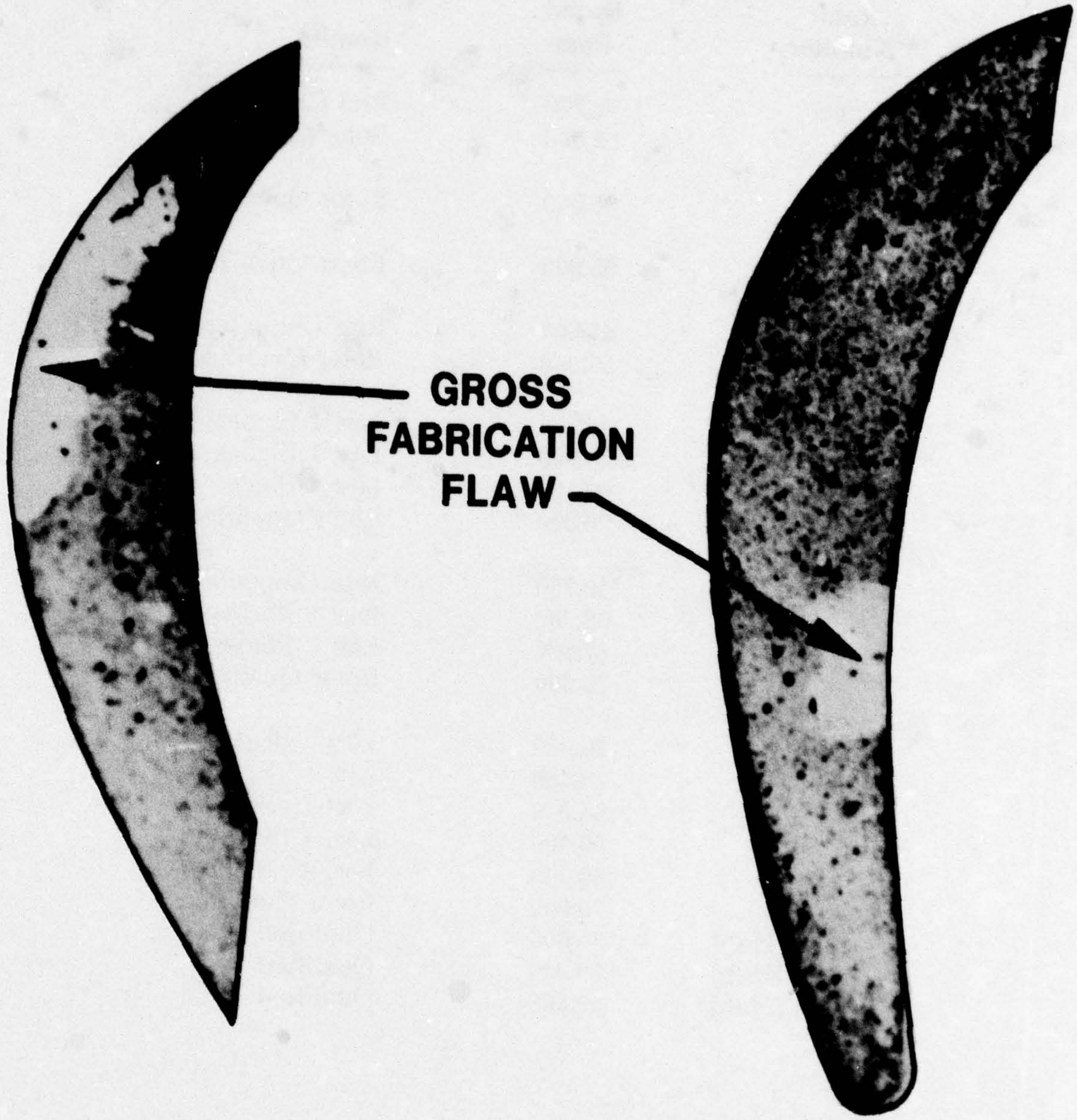


Figure 3.7 — Gross Flaws in Failed Blades.

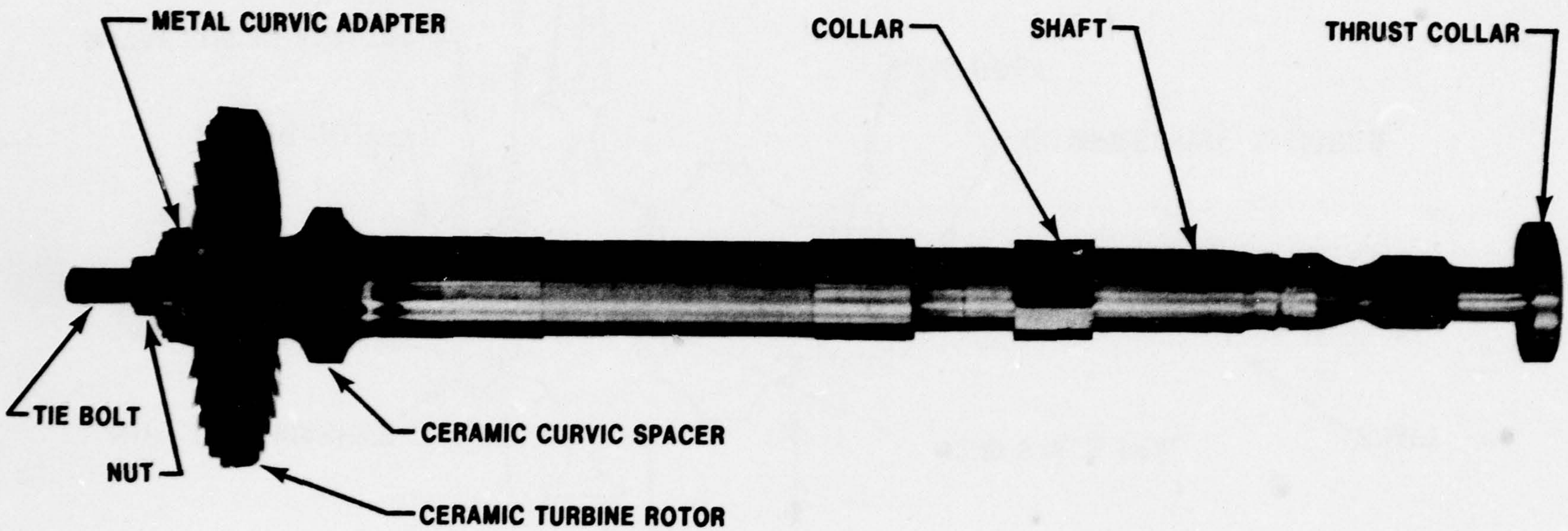


Figure 3.8 — Turbine Rotor and Shaft Assembly.

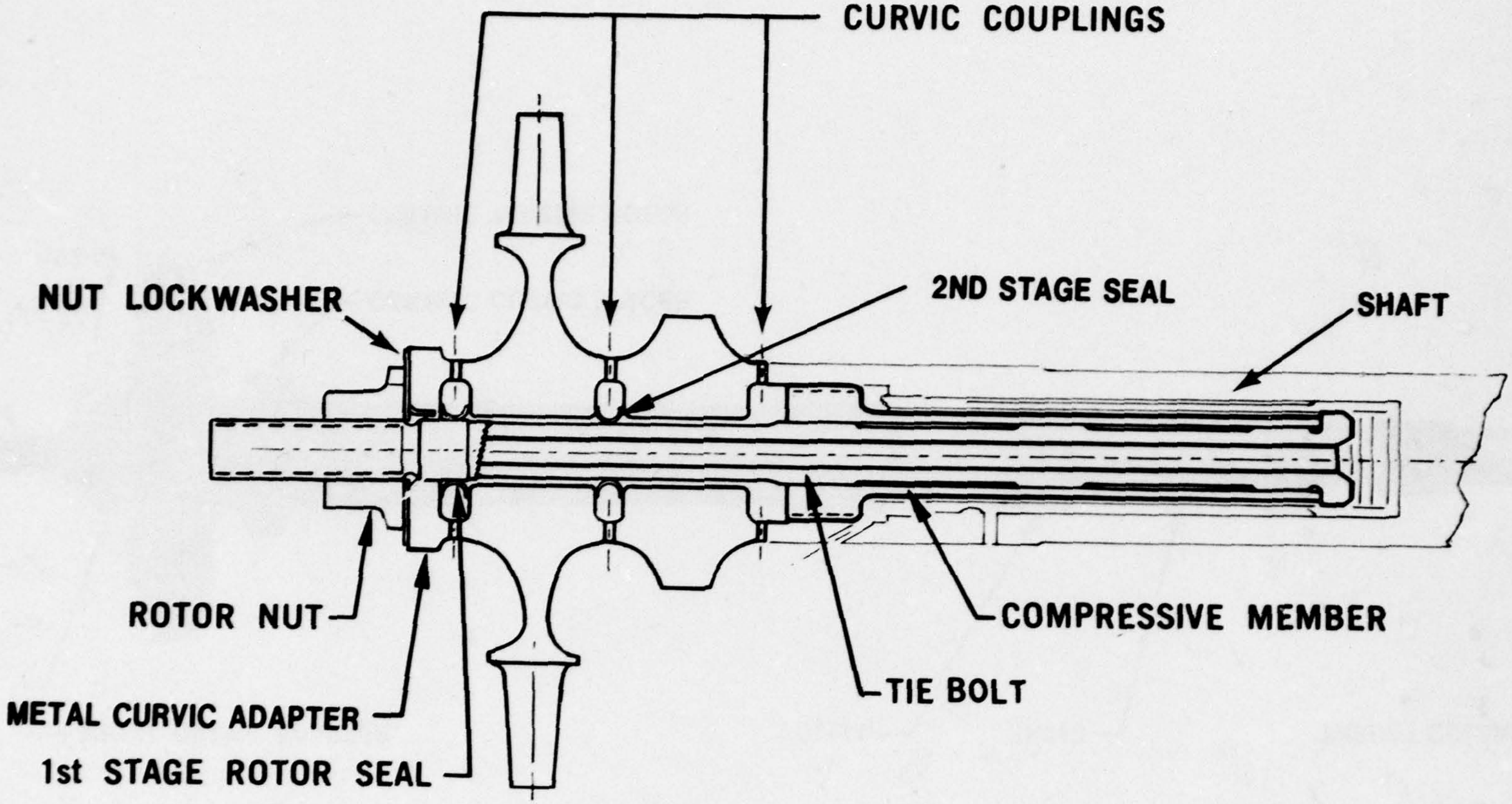


Figure 3.9 — Cross Section Drawing of Ceramic Spacer Attachment System.

corrected by removal of material at some other location than the rotor, for example from the metal curvic adapter, the rotor static imbalance would remain causing a locked in dynamic moment, although the overall rotor and shaft assembly would be balanced. To avoid this condition, the rotor static imbalance is corrected by removal of material from the rim of the rotor. If sufficient rim material is unavailable, then blades or portions of blades are removed. After the rotor is statically balanced any remaining rigid body moment in the assembly is corrected by removal of material from the balance collar. When the rotor assembly is balanced to within 0.003 oz-in in two planes it is ready for installation in the hot spin test rig.

The rotor and shaft assembly are installed in the test rig by removing the thrust collar from the shaft and inserting the shaft through the bearings. The rotor and associated hardware do not require disassembly, therefore, testing in the rig is conducted with the same balance as achieved in the balancing operation. This removes the uncertainty inherent in shaft systems requiring disassembly of the rotor and shaft for installation in the test rig.

Hot Spin Rig Development

To minimize cost during rotor testing-to-failure in the hot spin test rig, the original rotor attachment system consisted of a simple ceramic cone adapter for the rotor pilot and a metal attachment washer for the tie bolt pilot[9]. The ceramic cone was piloted in a mating metal cone which in turn was piloted on the shaft. The cone pilot system was intended to maintain rotor squareness and concentricity with the shaft while accommodating differences in thermal expansion between the ceramic rotor and metal shaft. However, tests on the ceramic cone attachment system showed that it did not adequately pilot the turbine wheel resulting in increased unbalance with increasing temperature. This was caused by the effect of friction in the cone pilot. The relative motion between the ceramic cone and mating metal cone, when the temperature changed, did not occur concentrically resulting in substantial unbalance force. As a result, the ceramic cone attachment system was abandoned in favor of the more expensive curvic coupling system.

The first tests in the hot spin rig with curvic couplings on the rotor were made with a metal curvic spacer and a short bolt made of Inconel 718 material as illustrated in Figure 3.10. This system was tested successfully for twenty-five hours with a bladeless hub in the hot spin test rig at 50,000 rpm and 1800°F rim temperature. Subsequent tests indicated that the thermal expansion differences between the silicon nitride hub and the Inconel X-718 short bolt were too large to be accommodated by the short bolt as explained in detail below; therefore, it was decided to use the engine tie bolt system for attaching the rotor to the shaft[10]. This attachment system is illustrated in Figure 3.9. A ceramic spacer, instead of the metal curvic spacer used with the short bolt, replaced the second stage rotor to allow testing a single rotor stage. This brought the hot spin test rig rotor attachment system in agreement with the as-designed engine system. Shaft dynamic problems have not occurred with this arrangement. Previous testing [11] had shown that a thin plating of gold functioned satisfactorily as a lubricating medium between metal and ceramic interfaces of the curvic coupling system and all metal curvic surfaces were electro plated with 0.0001 inch to 0.0002 inch of gold[9,10].

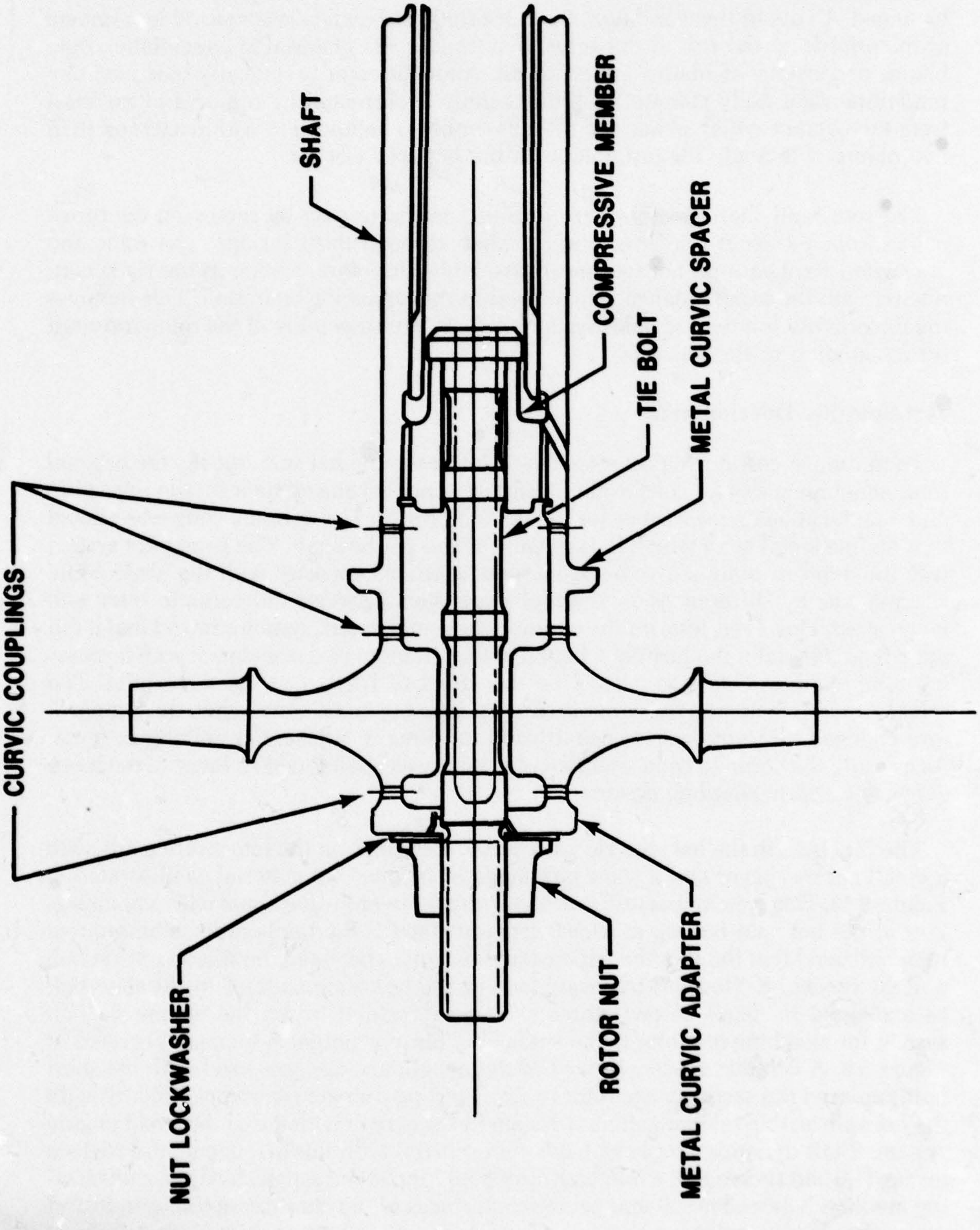


Figure 3.10 — Metal Curvic Spacer Attachment System.

The hot spin rig shroud used initially was made of a ceramic fiber insulation material[9,10,11]. This material is a high alumina ceramic fiber and is commercially available as moldable felt in sheets and pre-molded shapes. This material worked well for fast fracture tests where the test time was short. As the rig was developed for durability testing it became apparent that the ceramic fiber material required protection from high velocity gas erosion. A fused silica ceramic shroud material was suggested by the Ceramic Turbine Advisory Committee and a substitution was made as shown in Figure 3.11. A fused silica tube is contained in ceramic fiber insulation and is held in place by mechanically packing the insulation around it and bonding with high temperature cement. This arrangement has proven very durable. After 175 hours of continuous operation at a rotor rim temperature of 1800°F, the only distress on the fused silica shroud was an inconsequential hairline crack.

The present rotor and shaft assembly was previously shown in Figure 3.8. Prior to this reporting period the hot spin rig used a dummy wheel[9] simulating the compressor, and a compressor nut on the shaft. These two parts were used to duplicate compressor inertia effects on shaft dynamics. A critical shaft frequency was noted near 35,000 rpm. In general, reducing dead weight mass on a shaft increases the critical frequency and, therefore, the dummy wheel and compressor nut were removed from the shaft. This eliminated 1.56 pounds of dead weight, reducing the rotating mass to 5.10 pounds. This modification to the shaft assembly eliminated critical frequencies from the operating range, and in addition, the unbalanced load was reduced on the shaft after a rotor failure. This modification has resulted in elimination of damage to the shaft bearing journals from rotor failures as had been reported previously[11].

The tie bolt also underwent developmental changes. The initial purpose of hot spin rig testing was to conduct a series of controlled fast fracture rotor tests to correlate results with predictions based upon MOR material tests, finite element heat transfer and stress models, and Weibull analysis techniques for calculating fast fracture probability of failure[9]. For these tests a short bolt of H-11 tool steel was used to provide a brittle material which would fracture by a failing rotor allowing the rotor and associated hardware to leave the rotating shaft with a minimum of damage to the shaft journals and bearings. When it was realized that more information would be accumulated from long time durability tests, a bolt with sufficient life to avoid failure under any circumstances was chosen. The tie bolt material was then changed from H-11 material, to Inconel 718.

A twenty-five hour durability test on a rotor hub was run successfully with a short Inconel 718 material tie bolt, but a subsequent test indicated dynamic problems at relatively low speeds. This suggested that the bolt may have allowed the rotor to become unclamped. The spring rates for the short and long tie bolts used with the curvic coupling piloting system were calculated to be 580,000 lb/in for the short bolt, and 175,000 lb/in for the long bolt. The tie bolt design is based upon maintaining a 2000 pound clamping load on the rotor under hot operating conditions. To achieve this, the short bolt was stretched 0.0034 inches at assembly. The long tie bolt is initially stretched 0.026 inches. Therefore, the long tie bolt can accommodate 0.026 inches of axial expansion mismatch before the turbine rotor becomes unclamped versus 0.0034 inches for the short tie bolt. The long tie bolt was selected since it is much more forgiving of errors in predicting the system thermal mismatch.

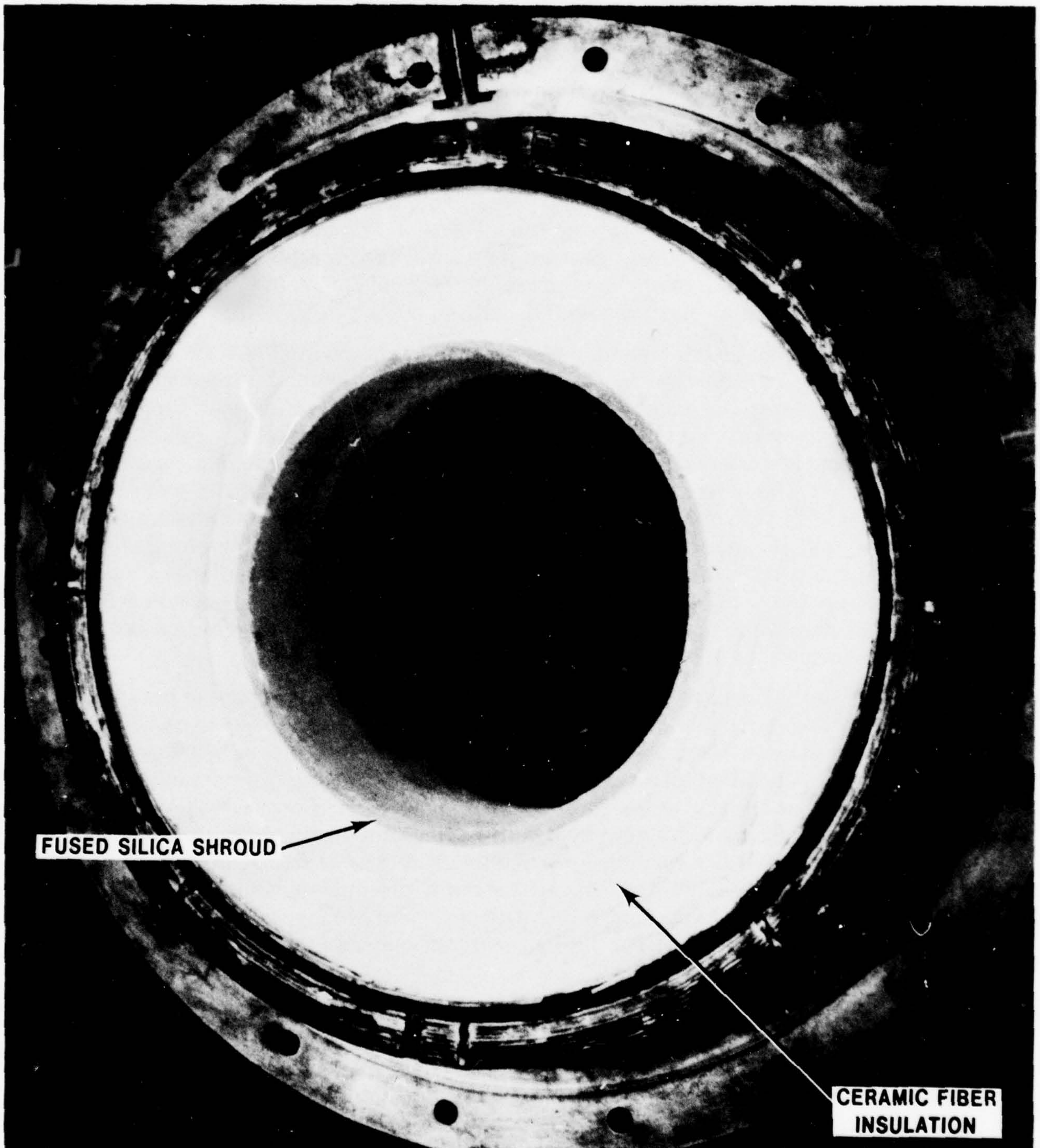


Figure 3.11 — Fused Silica Shroud

After successfully completing the twenty-five hour endurance test with four rotors at a rim temperature of 1800°F and a speed of 50,000 rpm, detailed in the next section, the rotors were disassembled from the shaft. When disassembling the rotors, three audible pings were heard. In two cases cracks were found using Zyglo™ techniques, as illustrated in Figure 3.6, in the curvic teeth of the rotor on the side mating with the metal curvic adapter. This indicated that the gold film lubricant may not be functioning as required. Radiation pyrometer and temperature sensitive paint measurements indicated that the metal curvic adapter temperature was 1650°F during the test. At this temperature the gold may react with the silicon nitride rotor to form gold silicides which would be a poor lubricant.

To correct this problem, it was necessary to reduce the temperature of the metal curvic adapter by more effective application of cooling air. The twenty-five hour endurance tests were run with the hot spin test rig nose cone insulator shown in Figure 3.12. This configuration allowed hot gases from the combustor discharge to circulate in the nose cone cavity and heat the curvic metal adapter. To reduce this circulation, an air deflector was added to the nose cone bell as illustrated in Figure 3.13. This directed the rotor bolt cooling air against the curvic metal adapter, and temperature measurements indicated that the adapter temperature was reduced to 1000°F.

25 Hour Rotor Durability Tests

To meet the objectivies of the Ford-ARPA program, testing of six duo-density silicon nitride turbine rotors was planned at a fixed speed and temperature in the hot spin test rig with a durability objective of twenty-five hours on each rotor. The results of the testing on the six rotors is summarized in Table 3.5.

The rotors had from 27 to 35½ blades remaining after finish processing. Blades were removed to eliminate flaws, and for balancing. Also, some were lost during cold spin qualifying.

All rotors that reached 50,000 rpm successfully in the hot spin rig, completed the twenty-five hour test. The two failures that occurred during acceleration to 50,000 rpm were with the metal curvic spacer and short bolt which indicated problems with this system and resulted in discontinuing its use.

Disassembly results, illustrated in Table 3.5, show that three of the rotors gave audible indications of cracking as the tie bolt was being unloaded. In two cases cracks were found in the curvic teeth with Zyglo™ techniques. The rotor that was disassembled without any indications of curvic teeth cracking was used for an additional 175 hour test to complete the 200 hour test objective.

The operating schedule for the twenty-five hour durability test is shown in Figure 3.14. The test procedure was to rotate the rotor cold at 2000 rpm and light-off the combustor. After the combustor was stabilized, speed was increased to 10,000 rpm and maintained for the test rig temperatures to stabilize. This was followed by an acceleration to 24,000 rpm, and stabilization of the rotor rim temperature at 1800°F.

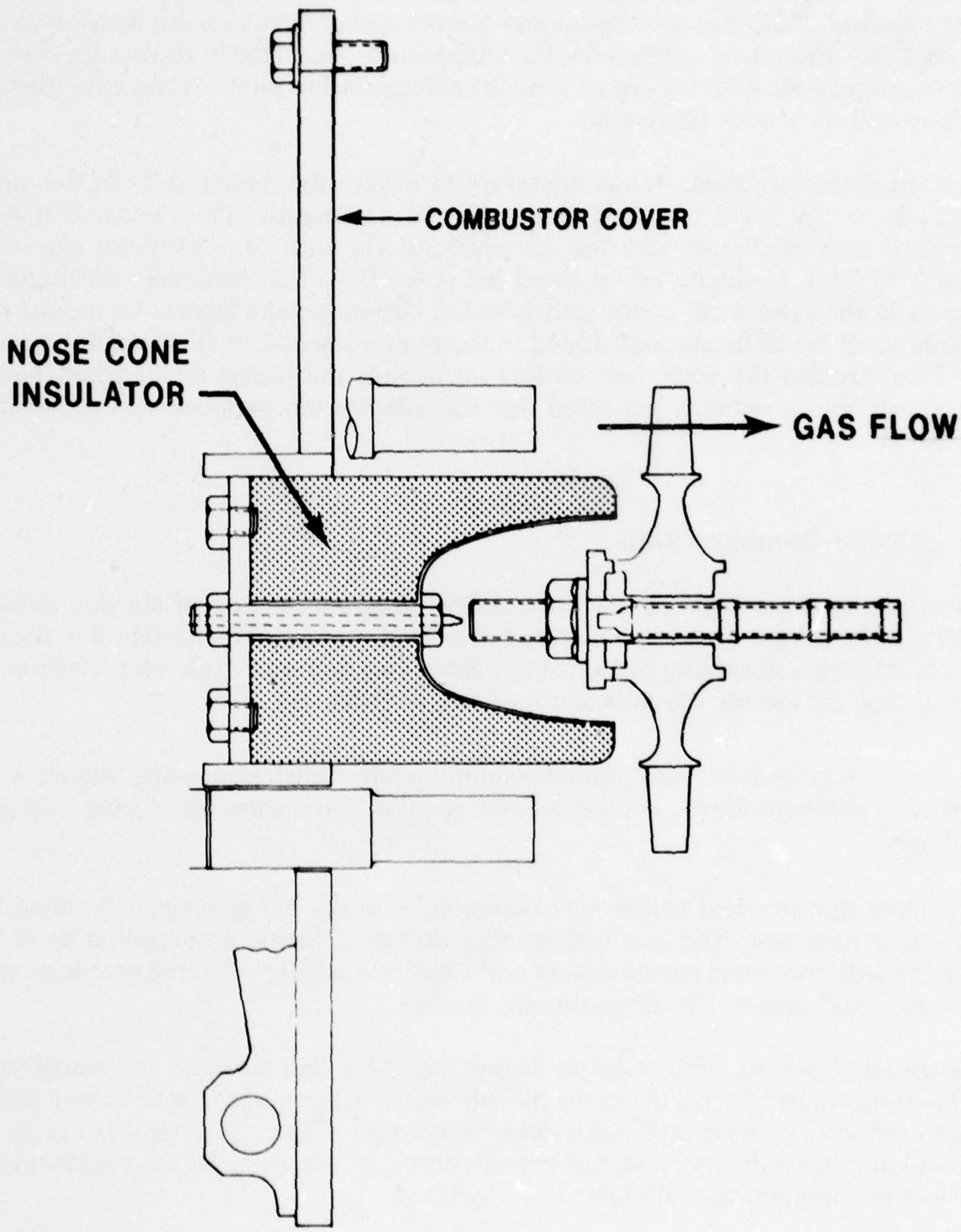


Figure 3.12 — Hot Spin Rig Nose Cone.

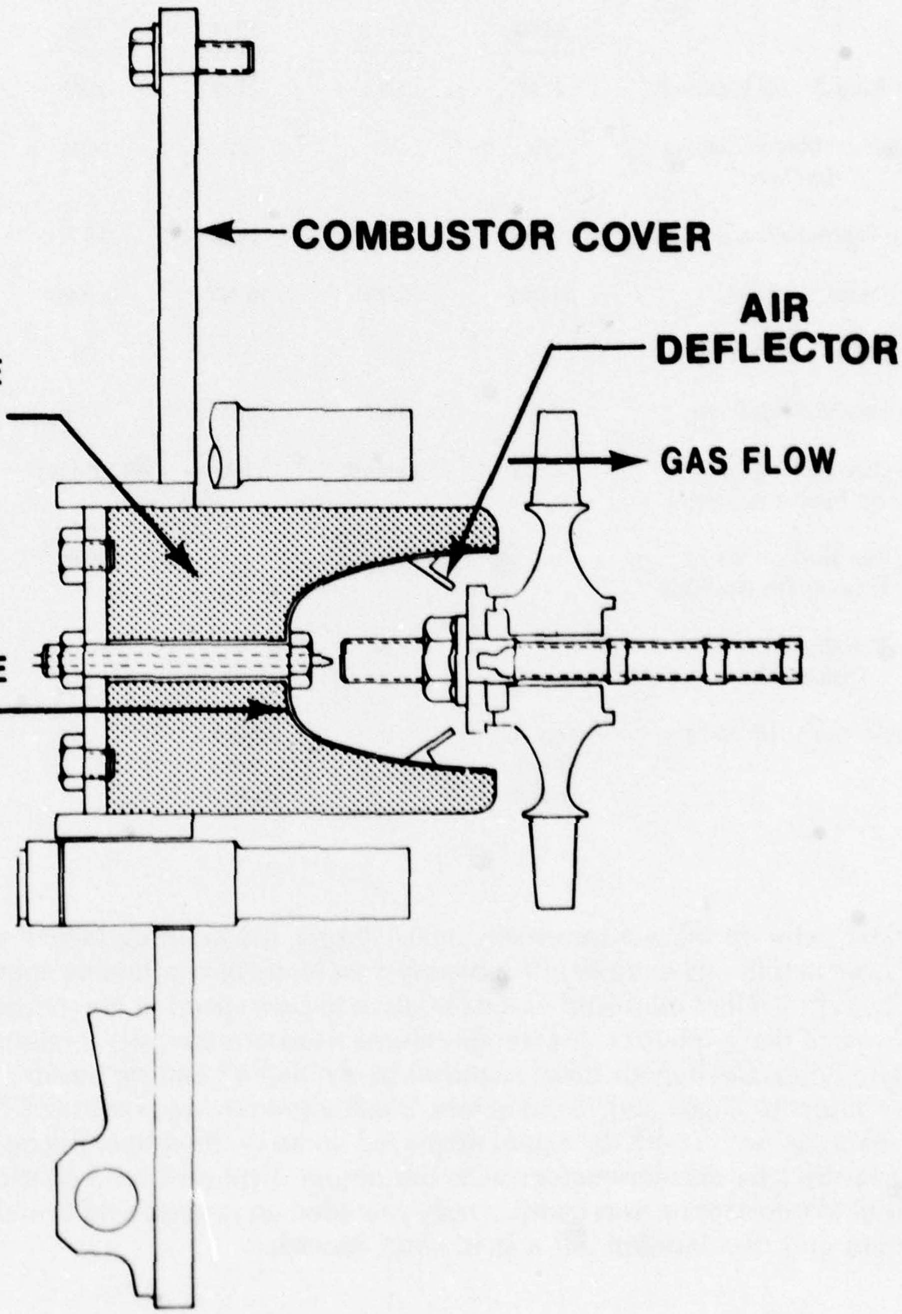


Figure 3.13 — Hot Spin Rig Nose Cone with Air Deflector

Table 3.5

25 Hour Ceramic Rotor Test Results

Rotor Serial Number

	1296	1324	1304	1287	1294	1306
Blade Ring Serial Number	2148	2032	2130	2045	1794	2033
Number of Blades During Hot Test	35	27	32	27	31	35½
Rim Temperature –°F	1800	1800	1800	1800	1800	1800
Speed — RPM	24,000	50,000	30,400	50,000	50,000	50,000
Time — Hours	—	25	—	25	25	25
Successful Shutdown	No	Yes	No	Yes	Yes	Yes
Attachment System — Curvic Spacer Material	Metal	Ceramic	Metal	Ceramic	Ceramic	Ceramic
Audible Indications of Cracking on Disassembly	—	Yes	—	Yes	Yes	No
Zyglo™ Indications After Disassembly	—	Yes	—	Yes	No	No
Probable Cause of Failure	Attach-ment System	—	Attach-ment System	—	—	—

Next, rotor speed was increased to 50,000 rpm, maintaining 1800°F rim temperature. These conditions were held for twenty-five hours of continuous operation. The shut-down procedure consisted of deceleration to zero speed in one minute and then shut down of the combustor. Rim temperatures were continuously monitored by an optical pyrometer. Cooling air flows required by the tie bolt and rig housing were monitored by pressure gages and manometers. Shaft vibration was indicated by a capacitance clearance probe with the signal displayed on an oscilloscope. Rig accelerations were measured by accelerometers with the output displayed on a spectral analyzer. All critical information was continuously recorded on magnetic tape, and during acceleration and deceleration, on a strip chart recorder.

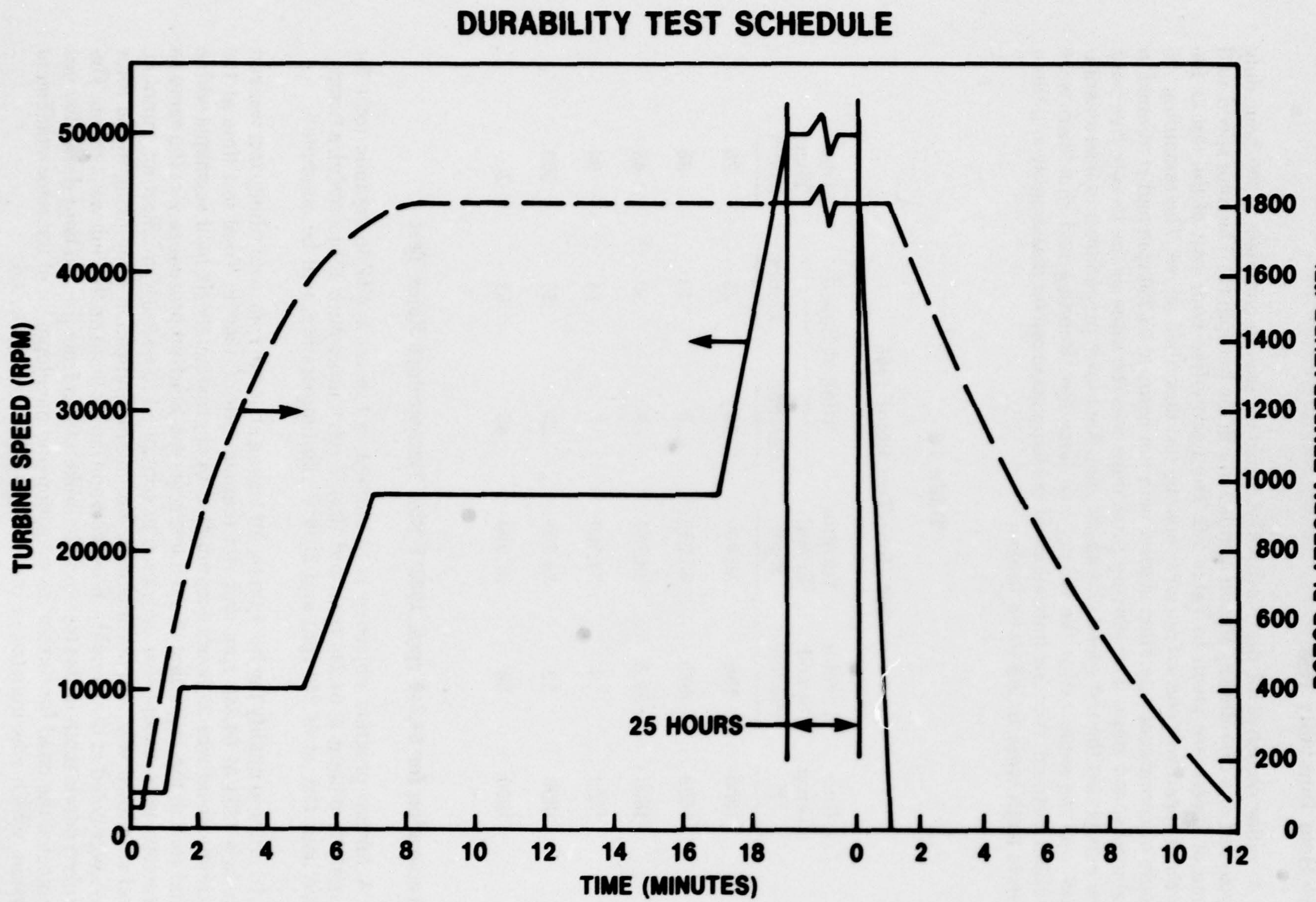


Figure 3.14 — 25 Hour Durability Test Schedule.

200 Hour Durability Test

A major objective of the Ford-ARPA program was to complete a 200 hour duty cycle test of a duo-density silicon nitride rotor in the hot spin rig. The rotor speed, and time at speed, are given in Table 3.6. The twenty-five hour part of the test at 100 percent speed was carried out as a separate test described above. The remaining 175 hours of continuous operation started with ten hours at 43,250 rpm and continued in reduced speed steps. The start-up procedure was the same as the twenty-five hour test except that the test speed was 43,250 rpm. Shutdown procedure and instrumentation was the same as for the twenty-five hour test. Running and shutdown were without incident. Audible indications of cracking occurred on disassembly and three curvic teeth were found to be broken.

Table 3.6

200 Hour Test Rotor 1306

Rim Temp °F	Turbine Speed Percent	Turbine Speed Rpm	Time at Speed Percent	Time at Speed Hours	Total Time Hours
1800	100	50,000	12	25	25
1800	86.5	43,250	5	10	35
1800	77.5	38,750	5	10	45
1800	69	34,500	7	14	59
1800	59	29,500	25	50	109
1800	55	27,500	46	91	200

Preparation for 64,240 rpm, 1800°F Rim Temperature Rotor Test

A further program objective is to attempt to test an available ceramic rotor for twenty-five hours at 64,240 rpm, and 1800°F rim temperature. If successful, a twenty-five hour test, at 64,240 rpm and 2250°F rim temperature, will be attempted.

In order to qualify the hot spin rig for testing at 64,240 rpm, a durability test was run on hub 1353 at 64,240 rpm and rim temperature of 1800°F. Total test time at 100 percent speed was 25 hours accumulated in approximately six hour segments with a cold start at the beginning of each test segment. Start-up procedure was the same as previous tests, except that acceleration continued to 64,240 rpm. Start-up, running, and shutdown was without incident. No audible indication of cracking in the rotor hub was noted at disassembly; however, one curvic tooth on the hub was broken. The broken curvic tooth in this test and the broken teeth from the 200 hour durability test indicated the need for further investigation and development of the rotor attachment system which was initiated at the end of this reporting period.

Engine Rotor Test

The last report (14) described testing and ultimate failure of rotor 1195 during a test in an 820 engine. Failure analysis indicated deterioration of the gold plate lubricant on the curvic metal adapter because of excessive temperature. This section will document the steps taken in subsequent tests to reduce the curvic metal adapter temperature.

To provide for more effective cooling of the metal curvic adapter, several engine modifications were made and are shown in Figure 3.15. To reduce circulation of 2500°F air between the turbine stator inner platform and the rotor blade platform, the clearance was reduced from 0.090 to 0.045 inches. To direct the 600-700°F bolt cooling air discharge over the metal curvic adapter, a cylinder was welded to the nose cone heat shield. The curvic adapter was also reduced in diameter to lower fin heat transfer effect. An additional thermocouple was placed in the revised heat shield cavity to monitor temperature.

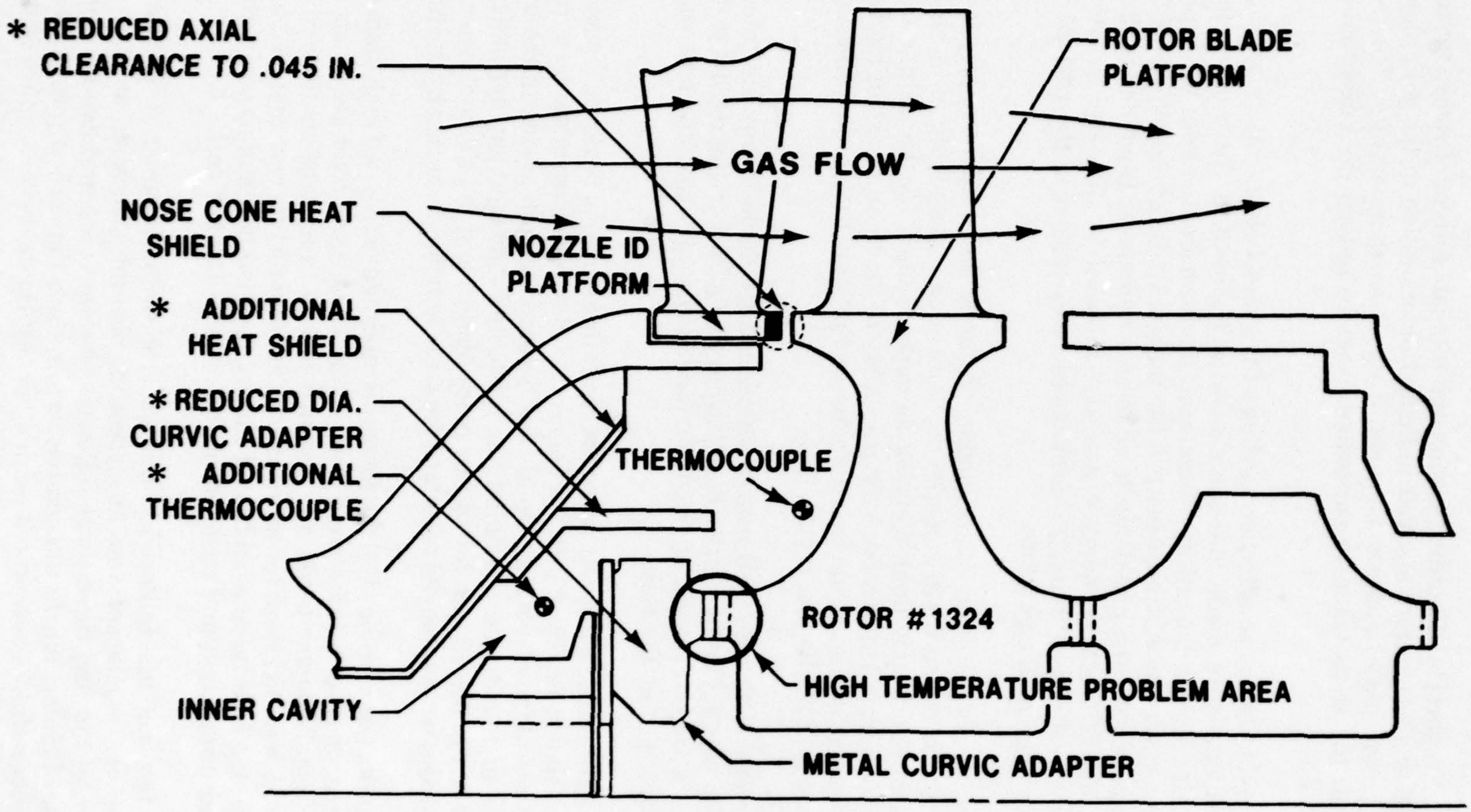
Although not required for reduction of curvic metal adapter temperature, additional engine changes were made: the burner can was modified to reduce carbon formation, and a new double spring mounting system for the turbine inlet thermocouples was installed to reduce the possibility of the thermocouples loading the nose cone. The rest of the engine was the same as that used to test rotor 1195, and is shown in Figure 3.11 of the last report. (14)

Additions to the test cell instrumentation were made to provide information for failure analysis. Engine output shaft torque was added to the recorded data, and all data input were recorded on magnetic tape so that an expanded time readout could be provided after the test.

The rotor used in this test was 1324, with three blades removed because of visual flaws as shown in Figure 3.16. All chips on blades and sharp edges on curvic coupling teeth were blended with diamond files before cold spin testing in the vacuum spin pit. The first cold spin test failed one blade and damaged another at 64,000 rpm. A second test to 69,480 rpm failed two more blades, and in addition, two and one half more blades were removed to reduce the large imbalance caused by the failed blades.

As in the test of rotor 1195, the rotor was mounted with a two inch diameter ceramic spacer in place of a full second stage rotor. The engine rotor shaft curvic teeth, the curvic metal adapter teeth, and the two turbine interstage seals were gold plated (0.0002 inches thickness) for lubrication. The rotor tie bolt was stretched to give a 4700 lb clamping load using a calibrated strain gaged washer, and a special fixture which allowed installation and removal of the rotor in the test cell.

The test schedule followed in this test is shown in Figure 3.17. The first attempt to light-off the combustor was unsuccessful. Several successive attempts resulted in ignition of the fuel three times followed by flame-outs, and two hot lights and shut downs. Modifications to the combustor to reduce the carbon forming tendency had been successfully checked out on another test rig; however, control of the burner in actual engine operation was very difficult. The combustor was replaced by the type



* CHANGES TO IMPROVE METAL CURVIC ADAPTER COOLING

Figure 3.15 — Engine Modifications for Improved Cooling of Metal Curvic Adapter.

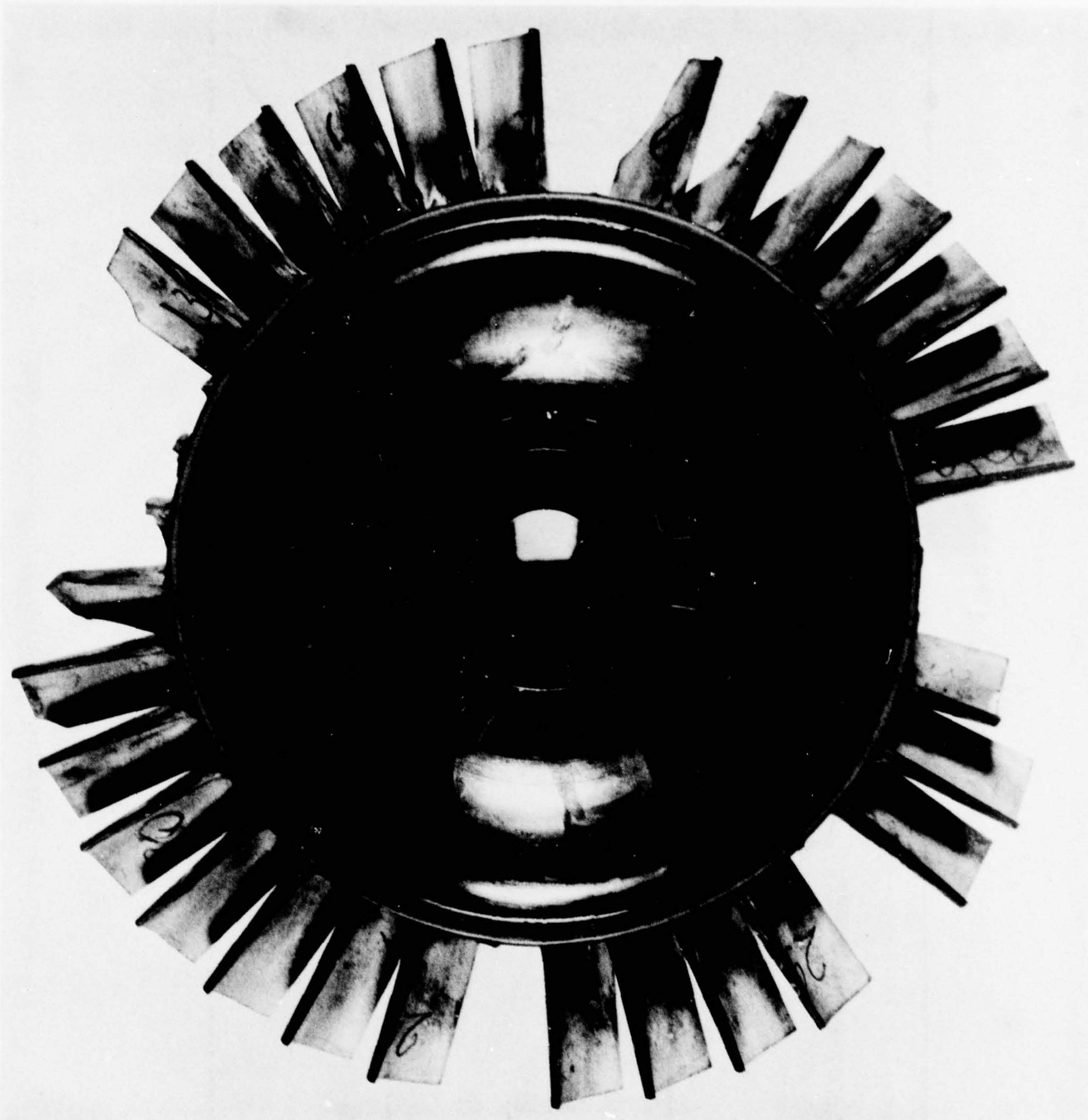


Figure 3.16 — Test Rotor Serial Number 1324.

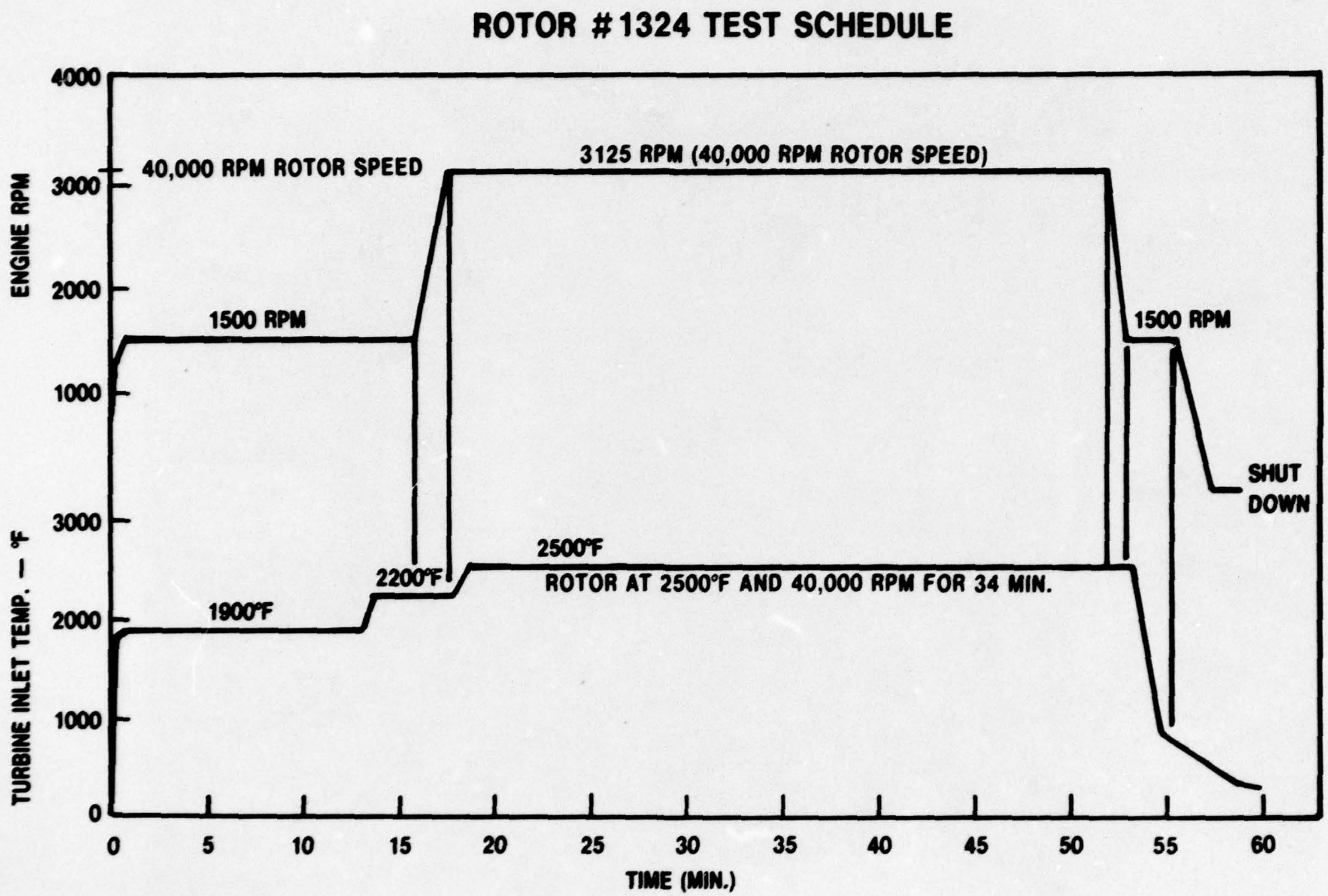


Figure 3.17 — Test Schedule — Metal Curvic Adapter Cooling Test.

previously used and a good light-off obtained. The rotor was held at 18,000 rpm and soaked at 1900°F turbine inlet temperature before an acceleration to 40,000 rpm was attempted. However, during acceleration an over-speed safety device malfunctioned and shut-down the engine . The safety unit was reset, the engine restarted, and the turbine inlet temperature raised slowly to 2200°F before accelerating to 40,000 rpm. After reaching speed, the turbine inlet temperature was raised to 2500°F and maintained at these conditions for thirty minutes. During this running period, data was recorded. The thermocouple monitoring the curvic metal adapter did not exceed 1116°F. Successful shut down was accomplished by holding turbine inlet temperature at 2500°F while reducing speed to 18,000 rpm; and then gradually reducing the turbine inlet temperature to 1200°F, when both speed and fuel were shut-down together.

All parts of the hot gas flow path were found to be in excellent condition after the test, and no overheating of the curvic metal adapter occurred. The gold plate lubricant on the metal curvic adapter was slightly tarnished but serviceable. Figure 3.18 shows an after test view of all rotating parts. Subsequent to this test, rotor 1324 and the mounting hardware were assembled in the hot spin test rig and successfully completed twenty-five hours of testing at 50,000 rpm and 1600°F rim temperature.

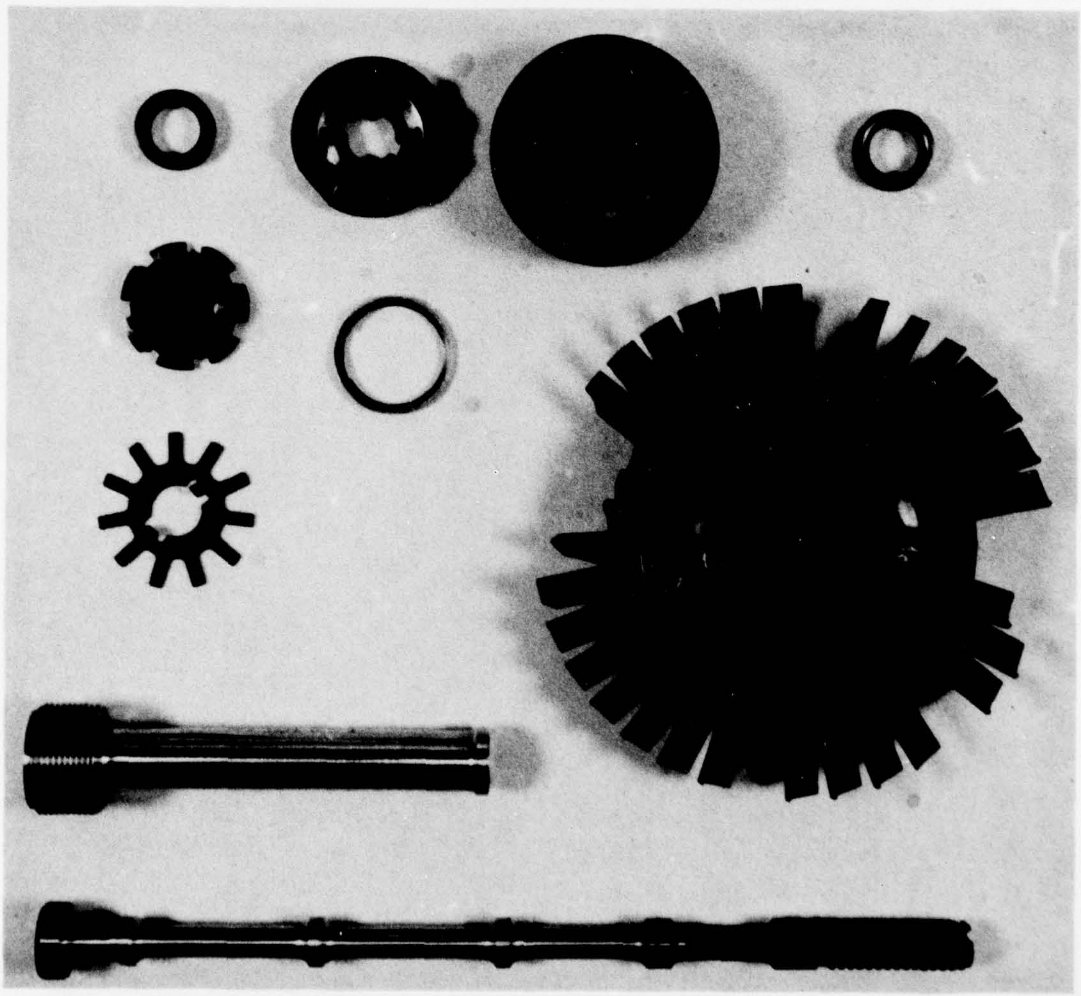


Figure 3.18 — Component Parts After Test.

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HIGH TEMPERATURE GAS TURBINE

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Technical Report AMMRC TR 79-12, May, 1979
71 pages, 21 illus., 6-tables, 14 references
Contract DAAG, 46-71-C-0162, ARPA Order Number
1849 Fourteenth Interim Report, September 30, 1977 to March 31, 1978

Key Words

Gas Turbine Engine
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Ceramics
High Temperature Materials
Silicon Nitride
Silicon Carbide
Non-Destructive Tests
Mechanical Properties

ABSTRACT

Modifications in the procedure for hot spin testing ceramic rotors resulted in several changes. The metal curvic spacer, used for mounting the ceramic turbine rotor on the test shaft, was replaced with a ceramic spacer. In addition, curvic coupling teeth were machined on inlet and exit sides of all rotors to accommodate change to a metal curvic washer for piloting of the rotor tie bolt. The short tie bolt for mounting the ceramic rotor to the hot spin test rig shaft was replaced with a long tie bolt as used in engine testing to provide margin for thermal expansion mismatch. The insulated nose cone used in the hot spin test rig was modified to redirect cooling air onto the metal curvic adapter for reduced temperature to relieve ceramic curvic tooth cracking. The complete surface area of the ceramic rotor hub was polished, in contrast to previous polishing of the centerbore and throat areas only. Of twenty-five rotors being proposed for hot testing, ten were inspected by dye-penetrant methods, dimensionally inspected, and curvic coupling contact patterns checked. Five have now completed hot testing; six are ready for test, and the remainder are in processing.

Four ceramic turbine rotors and one rotor hub were qualified for hot testing in the cold spin pit at 55,000 rpm, and three rotors and two rotor hubs were qualified to 70,000 rpm. Blades were lost on all rotors qualified to 70,000 rpm because of gross flaws in the blade cross section. From four to eleven blades per rotor were lost in qualification testing.

Six rotors were subjected to a twenty-five hour durability test in the hot spin test rig at 50,000 rpm and 1800°F rim temperature. Four rotors completed the test and two failed during acceleration to test speed. In several instances, post test rotor inspection revealed presence of curvic tooth cracking after disassembly from the test shaft. One of the successful rotors was operated an additional 175 hours to complete the objective of 200 hours at 1800°F rim tempera ture over a simulated duty cycle speed schedule.

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HIGH TEMPERATURE GAS TURBINE

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Non-Destructive Tests
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ABSTRACT

Modifications in the procedure for hot spin testing ceramic rotors resulted in several changes. The metal curvic spacer, used for mounting the ceramic turbine rotor on the test shaft, was replaced with a ceramic spacer. In addition, curvic coupling teeth were machined on inlet and exit sides of all rotors to accommodate change to a metal curvic washer for piloting of the rotor tie bolt. The short tie bolt for mounting the ceramic rotor to the hot spin test rig shaft was replaced with a long tie bolt as used in engine testing to provide margin for thermal expansion mismatch. The insulated nose cone used in the hot spin test rig was modified to redirect cooling air onto the metal curvic adapter for reduced temperature to relieve ceramic curvic tooth cracking. The complete surface area of the ceramic rotor hub was polished, in contrast to previous polishing of the centerbore and throat areas only. Of twenty-five rotors being proposed for hot testing, ten were inspected by dye-penetrant methods, dimensionally inspected, and curvic coupling contact patterns checked. Five have now completed hot testing; six are ready for test, and the remainder are in processing.

Four ceramic turbine rotors and one rotor hub were qualified for hot testing in the cold spin pit at 55,000 rpm, and three rotors and two rotor hubs were qualified to 70,000 rpm. Blades were lost on all rotors qualified to 70,000 rpm because of gross flaws in the blade cross section. From four to eleven blades per rotor were lost in qualification testing.

Six rotors were subjected to a twenty-five hour durability test in the hot spin test rig at 50,000 rpm and 1800°F rim temperature. Four rotors completed the test and two failed during acceleration to test speed. In several instances, post test rotor inspection revealed presence of curvic tooth cracking after disassembly from the test shaft. One of the successful rotors was operated an additional 175 hours to complete the objective of 200 hours at 1800°F rim tempera ture over a simulated duty cycle speed schedule.

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AD ______________

BRITTLE MATERIALS DESIGN
HIGH TEMPERATURE GAS TURBINE

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